TP 14631E

Detailed Plan and Design for Full-Scale Fire Tests of Thermally Protected 112J-Type Rail Tank-Cars

Prepared for

Transportation Development Centre
Transport Canada

by

Department of Mechanical and Materials Engineering
Queen's University
Kingston, Ontario

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Un sommaire français se trouve avant la table des matières.

Transport Canada Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.
TP14631E

2. Project No.
5642

3. Recipient's Catalogue No.

4. Title and Subtitle
Detailed Plan and Design for Full-Scale Fire Tests of Thermally Protected 112J-Type Rail Tank-Cars

5. Publication Date
November 2006

6. Performing Organization Document No.

7. Author(s)
A.M. Birk, C.R. Davison, and D.J. Poirier

8. Transport Canada File No.
2450-150-741

9. Performing Organization Name and Address

Queen's University
Department of Mechanical and Materials Engineering
McLaughlin Hall
Kingston, Ontario
K7L 3N6

10. PWGSC File No.
MTB-5-2-1153

11. PWGSC or Transport Canada Contract No.
T8200-5-5515/001/MTB

12. Sponsoring Agency Name and Address

Transportation Development Centre (TDC)
800 René Lévesque Blvd. West
Suite 600
Montreal, Quebec
H3B 1X9

13. Type of Publication and Period Covered
Final

14. Project Officer
Sesto Vespa

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

This report contains a detailed plan and design for full-scale fire testing of thermally protected 112J-type rail tank-cars. The testing is required to obtain data on a modern thermally protected rail tank-car subjected to an engulfing liquid hydrocarbon pool fire. Tests are planned for tank-cars with and without thermal protection system defects. This work is being done to assist in the development and validation of computer models of the thermal and structural response of tank-cars in fires. The testing will also help define allowable limits for thermal protection system defects.

A test site layout is proposed, including the fire pan, fire fuel storage and delivery system, test abort systems, control and observation bunkers, and estimated hazard distances. Detailed specifications and designs are provided for instrumentation of the tank-car and pool fire. The data acquisition and control system is designed and specified to meet the required sampling rates, and to provide safe and redundant control of the test. The plan includes a computer network allowing remote control and monitoring of the test. The proposed control system includes a real-time estimate of the time until failure of the test tank based on measured tank pressure and wall temperatures. Procedures and checklists are given to aid in the safe and successful completion of the tests from filling and purging to safely aborting in case of a malfunction.

This report can be used to start procurement of equipment and production of manufacturing drawings of required components. Remaining details will be finalized after the test site is determined and resources have been allocated.

17. Key Words
Rail tank-car, thermal protection, thermal protection defects, full-scale fire testing, engulfing pool fire, data acquisition, instrumentation, propane, LPG

18. Distribution Statement
Limited number of print copies available from the Transportation Development Centre. Also available online at www.tc.gc.ca/tdc/menu.htm

19. Security Classification (of this publication)
Unclassified

20. Security Classification (of this page)
Unclassified

21. Declassification (date)
—

22. No. of Pages
xx, 206

23. Price
Shipping/ Handling

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada
TP 14631E

2. N° de l'étude
5642

3. N° de catalogue du destinataire

4. Titre et sous-titre
Detailed Plan and Design for Full-Scale Fire Tests of Thermally Protected 112J-Type Rail Tank-Cars

5. Date de la publication
Novembre 2006

6. N° de document de l'organisme exécutant

7. Auteur(s)
A.M. Birk, C.R. Davison et D.J. Poirier

8. N° de dossier - Transports Canada
2450-150-741

9. Nom et adresse de l'organisme exécutant
Queen's University
Department of Mechanical and Materials Engineering
McLaughlin Hall
Kingston, Ontario
K7L 3N6

10. N° de dossier - TPSGC
MTB-5-2-1153

11. N° de contrat - TPSGC ou Transports Canada
T8200-5-5515/001/MTB

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
800, boul. René-Lévesque Ouest
Bureau 600
Montréal (Québec)
H3B 1X9

13. Genre de publication et période visée
Final

14. Agent de projet
Sesto Vespa

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

16. Résumé

Ce rapport contient un programme et un plan détaillés d'essais au feu en vraie grandeur de wagons-citernes de type 112J dotés d'une protection thermique. De tels essais sont nécessaires pour obtenir des données sur un wagon-citerne moderne doté d'une protection thermique, exposé à un bain de flammes enveloppantes produites par la combustion d'hydrocarbure liquide. Des essais sont prévus avec des citernes dont la protection thermique présente des défauts, et d'autres dont la protection thermique est intacte. Ces travaux visent à appuyer le développement et la validation de modèles informatiques du comportement thermique et structural de wagons-citernes enveloppés par des flammes. Les essais aideront aussi à définir les limites admissibles des défauts du système de protection thermique.

Le plan contient une proposition d'aménagement du lieu d'essai, y compris le plateau à feu, le système de stockage et de pompage du carburant pour le feu, le système d'interruption d'un essai, les abris blindés pour le personnel d'essai et les observateurs, et les distances sécuritaires à respecter. Des plans et spécifications détaillés sont fournis pour l'instrumentation du wagon-citerne et de la nappe de feu. Le système d'acquisition de données et de commande est conçu pour à la fois respecter les taux d'échantillonnage requis et assurer une commande sûre et redondante de l'essai. Le plan comprend un réseau informatique qui permet de commander et surveiller l'essai à distance. Le système de commande proposé comporte une évaluation en temps réel du temps de défaillance du wagon-citerne, à partir des valeurs mesurées de la pression dans la citerne et de la température de la paroi. Enfin, des procédures et des listes de contrôle sont proposées, pour des essais sûrs et réussis, depuis l'étape du remplissage et du vidage jusqu'à un abandon sans danger, en cas de problème.

Ce rapport peut servir de point de départ pour l'achat du matériel et la production des dessins de fabrication des composants nécessaires. Les détails qui manquent seront précisés après que le lieu d'essai aura été choisi et que les ressources nécessaires auront été affectées.

17. Mots clés
Wagon-citerne, protection thermique, défauts de protection thermique, essais au feu en vraie grandeur, bain de flammes enveloppantes, acquisition de données, instrumentation, propane, GPL

18. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires imprimés. Disponible également en ligne à www.tc.gc.ca/cdt/menu.htm

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	xx, 206	Port et manutention

Executive Summary

A full-scale fire test of a 127 m^3 (33,600 US gallon) rail tank-car has not been performed in North America since the early 1970s. Consequently no state-of-the-art, thermally protected, North American, rail tank-car has been fire tested under controlled conditions. This report presents a detailed plan to do such tests. The proposed test series will involve three to five instrumented rail tank-cars placed in an engulfing pool fire for 100 minutes. The test commodity will be propane or LPG.

The objectives of the tests include:

- i) obtain detailed thermal and mechanical data on a state-of-the-art thermally protected rail tank-car subjected to an engulfing pool fire for 100 minutes
- ii) obtain similar data for tank-cars with selected thermal protection defects
- iii) obtain detailed data on the effects of thermal protection defects

The above data will be used for further development of thermal and structural computer models for tank-cars in fires and for defining allowable limits for thermal protection system defects.

The tests will be performed in a remote location to minimise the hazards to surrounding populations if a tank-car should fail during the test. If all goes as per the plan, there will be no tank-car ruptures. The main hazards are fireball engulfment and thermal radiation, blast overpressure from the tank-car rupture, projectiles and possibly vapour cloud explosion if the released cloud has a delayed ignition. The safe distance from the tank-car is influenced by test site topography, but anything beyond a 3 km radius should be safe. The test location will be no closer than 5 km to the nearest public structure or public road. During a test, invited visitors will be located in a bunker at a radius of 2 km from the tank-car. The test personnel will be located in a bunker 1 km from the test tank-car, and the data acquisition equipment will be located at 50 m in a buried bunker.

The tank-car will be supported in the centre of a large liquid hydrocarbon pool fire. The tank-car wheels will be positioned at the pool surface. The standard tank-car will require additional openings to allow instrumentation cables and tubes to be inserted. Connections are also required to vent the propane vapour and drain the liquid to render the tank-car safe at the conclusion of the test.

Procedures to ensure a safe purge and fill and a safe and successful test are proposed. Checklists are provided to ensure that all systems and equipment are operational prior to starting a test, and to ensure the safety of test personnel and of the population surrounding the test site. Procedures to abort the test are given for various scenarios that could cause the test to terminate. The primary goal of the abort procedures is to ensure safety, and the secondary is to obtain the maximum sized data set or allow for a re-test. Hazards common to all construction sites and outdoor activities will be present during site preparation. During the test the most widespread hazards will result if the tank-car

ruptures, but fire heating and production of toxic smoke by the pool fire are also significant.

The pool fire is strongly influenced by wind, so the test will have to be performed under low wind conditions. The fire pan will contain water and fuel, JP-4, for the fire. The test could require as much as 182 m^3 (48,000 US gallons) of fuel, which will be pumped from storage tanks as required during the test. The fire is ignited with two propane burners situated at the upwind end of the fire pan.

The fire pan will sit on a concrete and gravel base to support the weight of the water, fuel, fire pan and tank-car. Cables running from the tank-car will be routed through pipes in the gravel to beyond the fire pan. All cables closer to the fire pan than the instrument bunker will be buried at least 30 cm deep, to shield them from the heat of the pool fire.

The tank-car will be instrumented with three planar arrays of thermocouples. Each array measures across the height and width of the liquid and vapour lading, as well as the wall and jacket temperatures. Additional thermocouples will be placed along the top of the tank-car and around the pressure relief valve. Tank-car pressure will be measured at four locations, to ensure that it is always known. A transient pressure transducer will also be connected to capture high-speed pressure transients. A video camera will be installed inside the tank-car to monitor liquid depth and liquid surface behaviour. This will provide fascinating and novel insight into the behaviour of the propane during relief valve opening.

The pool fire will be instrumented to determine the conditions the tank-car is exposed to. Thermocouples, directional fire thermometers and calorimeters will be employed to assess the fire intensity at various positions around the tank-car.

The pool fire will also be quantified by radiometers in the field around the pan. Radiometers placed further out will be used to assess the fireball strength in case of a tank-car failure. Blast gauges will also be positioned to determine the overpressure from a tank-car rupture, if one were to happen. Video and still cameras will be positioned in the field to record the test from various angles. This will provide a visual record of the pool fire behaviour to correlate to the temperatures measured in the fire and tank-car behaviour. A high-speed camera will also be installed to capture the dynamics of the tank-car behaviour.

Most of the data will be captured and recorded on two PC-based data acquisition systems. The systems will be programmed to display and record the data. The system will also handle automated control functions: starting the fire, turning on the fuel pumps, etc. The high-speed data from the blast gauges and transient pressure will be recorded by a PC-based data capture card. The data acquisition and control computers and electronics will be located in the instrument bunker 50 m from the test tank-car.

The data acquisition and control system will include a real-time failure analysis. The system will take the measured peak wall temperatures and tank-car pressure and use these to predict the time remaining until failure. The system will be based on a high-temperature stress rupture analysis. The output of this system will be used to decide if the test should proceed or if it should be aborted.

The data acquisition and control computers will be connected to the control bunker by a wireless network allowing the control bunker to monitor and control the test. Manual controls will be available to override any critical functions, such as fuel flow and tank-car drains. The manual controls will be connected to the control bunker with copper wire. Having test control possible over two independent systems reduces the possibility that complete control of the test will be lost.

This report provides a detailed design of the proposed fire testing of 127 m^3 propane rail tank-cars. Final design will not be possible until the test location and resources have been determined.

Sommaire

Le dernier essai au feu en vraie grandeur d'un wagon-citerne d'une capacité de 127 m^3 (33 600 gallons US) réalisé en Amérique du Nord remonte au début des années 1970. Ainsi, aucun wagon-citerne nord-américain de technologie récente, doté d'une protection thermique, n'a été soumis à des essais au feu dans des conditions contrôlées. Ce rapport présente un plan détaillé pour la réalisation de tels essais. La série d'essais proposée comportera trois à cinq wagons-citernes instrumentés, exposés à un bain de flammes enveloppantes pendant 100 minutes. Le produit utilisé pour les essais sera du propane ou du GPL.

Les essais ont pour objet ce qui suit :

i) obtenir des données thermiques et mécaniques sur un wagon-citerne de technologie récente doté d'une protection thermique, exposé à un bain de flammes enveloppantes pendant 100 minutes
ii) obtenir des données semblables pour des wagons-citernes présentant des défauts de protection thermique choisis
iii) obtenir des données détaillées sur les effets des défauts de protection thermique

Les données ci-dessus seront utilisées pour poursuivre le développement de modèles informatiques du comportement thermique et structural de wagons-citernes enveloppés par des flammes et pour définir les limites admissibles des défauts du système de protection thermique.

Les essais auront lieu dans un endroit isolé afin de réduire au minimum les risques pour la population environnante en cas de rupture d'une citerne au cours de l'essai. Si tout fonctionne comme prévu, aucune rupture ne devrait survenir. Les principaux risques sont l'enveloppement par une boule de feu et le rayonnement thermique, la surpression (onde de souffle) consécutive à la rupture d'un wagon-citerne, la projection de débris et la déflagration possible d'un nuage de vapeur, dans le cas où le nuage libéré tarderait à s'enflammer. La distance sécuritaire à respecter par rapport au wagon-citerne dépend de la topographie du lieu d'essai, mais un rayon de 3 km devrait suffire à parer à tout danger. Le lieu d'essai doit se trouver à un rayon d'au moins 5 km de l'ouvrage ou du chemin public le plus près. Les personnes invitées à assister à un essai doivent se trouver dans un abri blindé à une distance de 2 km du wagon-citerne. Un autre abri blindé sera prévu pour le personnel d'essai, à 1 km du wagon-citerne, et le matériel d'acquisition des données sera placé dans un caisson enfoui à une distance de 50 m.

Le wagon-citerne sera au centre d'un grand feu de nappe d'hydrocarbure liquide, ses roues au niveau de la surface de la nappe. Des orifices devront être pratiqués dans le wagon-citerne standard pour le passage des câbles et canalisations d'instrumentation. Des canalisations de raccordement devront aussi être prévues pour l'évacuation de la vapeur

de propane et l'écoulement du liquide, afin d'éliminer tout risque relié au wagon-citerne, à la fin de l'essai.

Le rapport propose également des procédures pour un vidage et un remplissage sans danger, et un essai sûr et réussi. Des listes de contrôle sont fournies, qui aideront à vérifier que tous les systèmes et appareils sont opérationnels avant le début d'un essai, et à garantir la sécurité du personnel d'essai et de la population environnante. Des procédures pour l'abandon de l'essai ont aussi été préparées, selon divers scénarios susceptibles de forcer un arrêt prématuré de l'essai. Le but principal des procédures d'abandon est de garantir la sécurité, et le but secondaire est d'obtenir l'ensemble de données le plus vaste possible ou de permettre une reprise de l'essai. Les risques liés à la préparation du site sont les risques communs à tous les chantiers de construction et aux activités extérieures. Pendant l'essai comme tel, les dangers les plus graves résulteront de la rupture du wagon-citerne, mais la chaleur du feu et le dégagement de fumée toxique sont aussi des risques non négligeables.

Comme les flammes sont fortement influencées par le vent, l'essai devra avoir lieu par vent faible. Le plateau à feu contiendra de l'eau et du carburant, JP-4, pour le feu. L'essai pourrait nécessiter pas moins de 182 m^3 (48 000 gallons US) de carburant, qui sera pompé de réservoirs de stockage, au fur et à mesure de l'essai. Le feu sera allumé par deux brûleurs au propane situés au vent par rapport au plateau à feu.

Le plateau à feu reposera sur une base en béton et en gravier assez solide pour supporter le poids de l'eau, du carburant, du plateau à feu et du wagon-citerne. Des câbles partant du wagon-citerne seront acheminés par des canalisations dans le gravier jusqu'à l'extérieur du plateau à feu. Toutes les longueurs de câbles entre le plateau à feu et le caisson à instruments seront enfouies à une profondeur d'au moins 30 cm, de façon à être protégées de la chaleur du feu.

L'instrumentation du wagon-citerne comportera des réseaux plans de thermocouples. Ces réseaux mesureront la température du chargement de liquide et de vapeur, en hauteur et en largeur, et les températures de la paroi et de la jaquette. D'autres thermocouples seront placés sur le dessus de la citerne et autour de la soupape de sûreté. La pression à l'intérieur de la citerne sera mesurée à quatre endroits, de sorte que l'on sera assuré de toujours connaître cette donnée. Un transducteur de pression transitoire sera aussi installé, qui captera les transitoires de pression très brefs. Une caméra vidéo sera installée à l'intérieur du wagon-citerne pour surveiller le comportement du volume et de la surface du liquide. Les images inédites que prendra cette caméra permettront de percer le secret du comportement du propane pendant l'ouverture de la soupape de sûreté.

L'instrumentation de la nappe de feu permettra aux chercheurs de déterminer les conditions auxquelles le wagon-citerne sera exposé. Des thermocouples, des thermomètres à feu directionnels et des calorimètres seront utilisés pour mesurer l'intensité du feu à divers endroits autour du wagon-citerne.

La nappe de feu sera aussi l'objet de mesures, grâce à des radiomètres placés sur le terrain entourant le plateau à feu. Les radiomètres éloignés serviront à évaluer l'intensité de la boule de feu en cas de rupture de la citerne. Des indicateurs de pression seront mis en place pour mesurer la surpression (onde de souffle) causée par la rupture éventuelle d'un wagon-citerne. Des caméras vidéo et des appareils photo prendront des images de l'essai sous divers angles. On obtiendra ainsi un enregistrement visuel du comportement de la nappe de feu, que l'on pourra corréler avec les températures mesurées dans le feu et avec le comportement du wagon-citerne. De plus, une caméra à grande vitesse enregistrera la dynamique du comportement du wagon-citerne.

Deux systèmes d'acquisition de données de type PC assureront la saisie et le stockage de la plupart des données. Ces systèmes seront programmés pour afficher et enregistrer les données. Le système pilotera également des fonctions de commande automatisée : allumage du feu, mise en marche des pompes à carburant, etc. Les données à grande vitesse des indicateurs de pression de souffle et les valeurs de pression transitoire seront enregistrées par une carte de saisie de données sur PC. Les ordinateurs d'acquisition des données et de commande, et l'appareillage électronique seront placés dans le caisson à instruments, à 50 m du wagon-citerne d'essai.

Le système d'acquisition de données et de commande comprendra un logiciel d'analyse de défaillance en temps réel. Le système utilisera les valeurs maximales mesurées de température de la paroi et de pression dans le wagon-citerne, pour prédire le temps de défaillance. Il sera développé à partir d'une analyse de la rupture par fluage à haute température. Les résultats de cette analyse aideront les chercheurs à décider si l'essai doit être poursuivi ou s'il y a lieu de l'abandonner.

Les ordinateurs d'acquisition de données et de commande seront reliés à l'abri du personnel d'essai par un réseau sans fil, ce qui permettra au personnel de surveiller et commander l'essai. Des commandes manuelles seront prévues, qui auront priorité sur les fonctions critiques, comme le pompage du carburant et l'écoulement du contenu de la citerne. Ces commandes manuelles seront reliées à l'abri du personnel d'essai par un fil de cuivre. Grâce à ces deux systèmes de commande indépendants, il est peu probable que les chercheurs perdent complètement la maîtrise de l'essai.

Ce rapport présente un plan détaillé de l'essai au feu proposé de wagons-citernes de propane d'une capacité de 127 m^3. Un plan définitif ne pourra être élaboré que lorsque l'on connaîtra le lieu de l'essai et les ressources mises à disposition.

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Glossary

AAR:	The **A**ssociation of **A**merican **R**ailroads
Baseline test:	Fire test of rail tank-car with no thermal defects
BLEVE:	**B**oiling **l**iquid **e**xpanding **v**apour **e**xplosion
DAC:	**D**ata **a**cquisition and **c**ontrol
DFT:	**D**irectional **f**ire **t**hermometer
Gallon:	US Gallon – 3.785 Litres
kPaG:	**K**ilo**pa**scals **g**auge – metric measure of pressure relative to atmosphere
NPT:	**N**ational **p**ipe **t**hread – standard piping sizes
Pre-test burn:	Ignition of the pool fire prior to the installation of test tank-cars with object of assessing the fire and test system
PSIG:	**P**ounds per square **i**nch **g**auge – measure of pressure relative to atmospheric pressure
PSIA:	**P**ounds per **s**quare **i**nch **a**bsolute – absolute measure of pressure
PRV:	**P**ressure **R**elief **V**alve [For the purpose of this report rail tank-car set point was assumed to be 1935 kPaG (280 PSIG)]
Purge:	The process of replacing air in a tank with propane vapour to prevent over pressurisation
RAX tests:	Propane rail tank-car fire tests performed by US Federal Railroad Administration/Department of Transportation and Railway Progress Institute – Association of American Railroads
RAX 201:	Fire test on un-insulated 128 m^3 propane railcar in July 1973
RAX 201:	Fire test on insulated 128 m^3 propane rail tank-car in December 1973
Thermal Defect:	Area of reduced insulation effectiveness on a tank-car

1. Introduction

A full-scale fire test of a 127 m^3 (33,600 gallon) rail tank-car, filled with propane, has not been performed since the RAX tests in 1973. The full-scale RAX tests consisted of one unprotected rail tank-car and one with a spray on thermal coating. No fire tests have been performed on state-of-the-art, thermally protected, North American, propane rail tank-cars. This proposed test series will expose 112J340W type tank-cars to an engulfing pool fire, similar to those used in the RAX tests. After the baseline test the thermal protection will be modified to assess the effect of thermal protection defects. The tank-car will require minor modifications from the standard design to allow instrumentation and for valving, to render the tank-car safe after the test. These modifications will not alter the survivability or response of the tank-car to the engulfing fire.

This report provides details on the test setup, tank-car and field instrumentation, and data acquisition and control. It also provides test procedures, site layouts and preliminary designs of the fire pan and other components. The layout and component drawings of the designs are included in Appendix A.

1.1. Objectives

The objectives of the test series include:

1. Obtain detailed data on the response of a modern propane rail tank-car subjected to an engulfing hydrocarbon pool fire.
2. Obtain similar data for tank-cars with defined thermal protection defects.
3. Obtain detailed data that can be used to further develop and validate computer models.
4. Demonstrate the survivability of tank-cars with thermal protection defects in a pool fire.

Additionally, if a tank-car should fail:

1. Obtain blast data from a rail tank-car failing under fire conditions.
2. Obtain thermal data from the fireball produced by the failing tank-car.
3. Record projectile distances.
4. Use hazards data to further refine safe distances from rail tank-cars with the potential for a boiling liquid expanding vapour explosion (BLEVE).

To support these objectives it is necessary to quantify the pool fire in detail, and define the conditions under which the test occurred. This allows modeling and comparison to other tests and actual accidents.

1.2. Test Overview

The tank-car will be placed in the centre of a 24 m by 9 m pool fire for 100 minutes. Each side of the tank-car will have 3 m between itself and the edge of the pool. The fire tests will last 100 minutes. Data will be recorded until the fire has burnt out and the tank-car is vented to atmospheric pressure.

Four tests are proposed, as follows:

1. Baseline – 112J340W thermally protected tank-car with no thermal protection system defects – tank-car in new condition except for modifications required to perform test.
2. Small axial thermal defect.
3. Small circumferential defect.
4. Medium axial or circumferential defect.

The locations and relative sizes of the thermal defects are shown in Figure 1. Table 1 provides the dimensions of the defects along the surface of the tank-car, the area of the defect and the fraction of the tank-car surface the defect covers. The midline of the axial defects is at the 90% fill level. The circumferential defects run from the top to bottom of the tank-car, on one side. The defects are located on the downwind end of the tank-car, to ensure consistent flame engulfment, and are shifted from the centre to avoid the fittings at the top centre of the tank-car, including the pressure relief valve (PRV). This prevents alterations in the PRV behaviour due to increased heating, and removes the effect of the fittings on the heat transfer in the defect.

Table 1: Thermal defect specifications

Defect	Length Along Tank-car Axis (m)	Length Around Tank-car (m)	Area (m^2)	Fraction of Tank-car Area
Small Axial	7.20	0.50	3.6	2%
Small Circumferential	0.76	4.79	3.6	2%
Medium Axial	7.20	1.00	7.2	4%
Medium Circumferential	1.53	4.79	7.3	4%

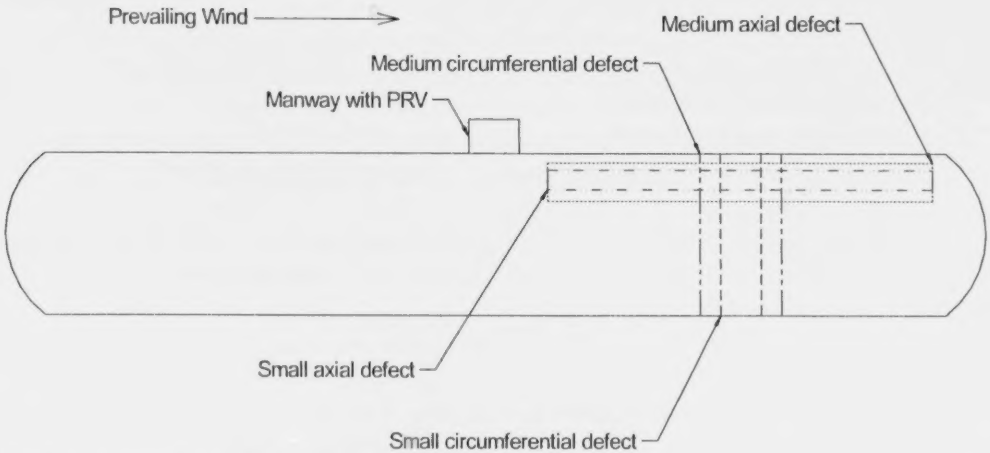


Figure 1: Location of thermal defects on tank-car

If time and budget are available, five tests could be performed to examine both the medium axial and circumferential defects. The axial defect will allow for significant heating of a large section of the tank-car. The top of the medium axial defect is above the 95% fill level so it will initially be in the vapour space. The bottom is just below the 80% fill level, and the entire defect will likely be in the vapour space for a significant portion of the test. This allows the tank-car wall to heat, but reduces the energy input into the tank-car lading. The radial defect will cover more of the liquid space, preventing high temperatures over a large area, but increasing the heat transfer into the tank-car lading. Further details on the defect locations and instrumentation are provided in the drawing package (Appendix A) and section 5.1.

In addition to the fire tests of the rail tank-cars, two or more pre-test burns will be carried out. All data acquisition and control (DAC) channels will be recorded and control system functioning verified. The fire sensors will be connected to ensure they function and to quantify the fire. A smaller tank, 1900 or 3800 L (500 or 1000 gallons), could be filled with water and some of the tank-car sensors and the drain and vent lines connected, for additional system verification. The water filled tank-car should not be allowed to pressurise but it can be used as a crude calorimeter to confirm fire heat transfer rates. The pre-test will also verify the ignition system and refine the estimates of the fuel burn-off rate. The pre-test will not last 100 minutes, but it should allow the pool fire to come to steady state and an estimate of the instrument bunker heating to be made.

1.3. Test Site

The site will have to be in a remote area with a 5 km uninhabited radius around the tank location. The geography of the area will help determine the exact safe distances required. The main features of the test site are:

1. Fire pan and test tank-car – centred on test site.
2. Instrumentation bunker – 50 m from test tank-car containing data acquisition and control equipment.
3. Control bunker – 1000 m from test tank-car for personnel involved in running the test.
4. Visitor bunker – 2000 m from test for visitors and personnel not involved in running the test.
5. Fuel supply tanks – 200 m from test tank-car to provide JP-4 to fuel the pool fire.
6. Camera shelters – at 200 m and 500 m distances from test tank-car to house video, still and high-speed cameras.

Wind is a problem for this kind of open fire testing. A site should be selected that has low wind speeds. Prevailing wind directions must be considered when setting up the test site.

2. Test Tank-Car and Site Setup

2.1. Test Tank

The test tank-car is expected to be a class 112J340W rail tank-car with the following specifications:

Tank-car Length (Inside): 18.4 m (725 inches)
Inside Diameter: 3.02 m (118 ¾ inches)
Plate Thickness: 15.9 mm ($^5/_8$ inch)
Mass Empty: 45,700 kg (100,800 pounds)
Mass 95% Full, Propane: 106,000 kg (233,700 pounds)

The tank-car will arrive at the site on a specialised flatbed truck. The tank-car may be shipped to the vicinity of the test site by rail. A road will be required to the fire pan, which can support the flatbed truck and tank-car. Once beside the fire pan, the tank car will be transferred to the supports by a crane.

The tank must be supported in a pool fire for 100 minutes and the test site arranged to ensure the safety of all personnel and the surrounding environment, should the tank suffer a BLEVE failure. It should be noted that tank failure is not expected in this test series. It may be decided to abort the test if a tank comes close to failure conditions.

The required data must be recorded and preserved in the event of a BLEVE and, as much as possible, equipment must be preserved. Figure 2 shows the layout of the test site including bunker and camera locations. Details on the layout of particular items are expanded in subsequent sections of the report.

2.2. Rail Tank-Car Support Structure

The tank-car will be supported on lengths of rail sitting on 25.4 cm (10 inch) square steel tubes, as shown in Figure 3. One of these structures will be placed at either end of the rail tank-car. The top of the rail will be level with the lower limit of the JP-4. This will keep the support structure immersed in liquid during the test, preventing it from heating to the point when the steel strength is reduced. To distribute the weight over the fire pan base and supporting concrete, a 1.3 cm (½ inch) steel plate will be placed under the 25.4 cm (10 inch) square tubes with 1.3 cm (½ inch) thick walls.

The worst case was used to verify the structure could resist buckling, would not exceed the yield strength of steel, and that beam deflections would be insignificant. The loaded tank-car was assumed to weigh 1,060 kN. The calculations are presented in Appendix B. The calculations are conservative, since they assume the load is on a single member, but even if the original load produced this effect as soon as elastic deformation occurs the load would be distributed over a larger area. A safety factor of 5.1 was calculated for buckling and 3.7 for yield strength.

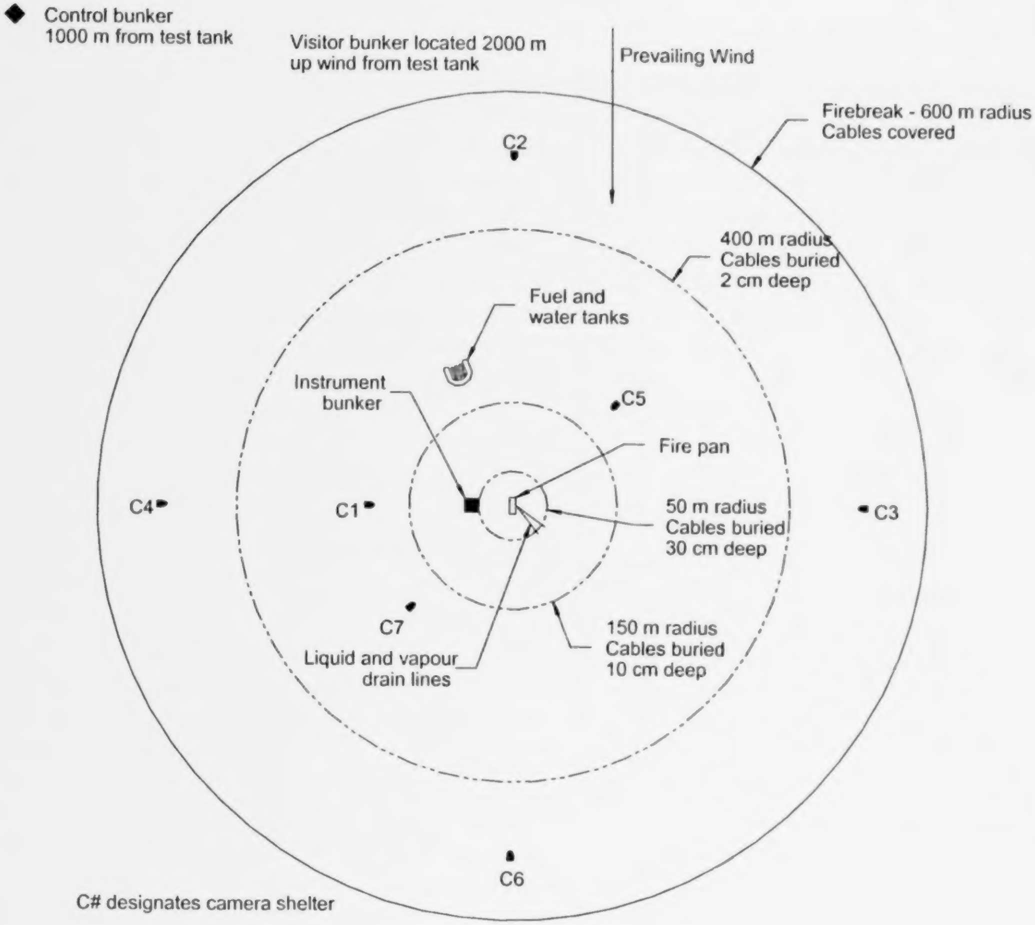

Control bunker
1000 m from test tank
Visitor bunker located 2000 m
up wind from test tank
Prevailing Wind
Firebreak - 600 m radius
Cables covered
C2
400 m radius
Cables buried
2 cm deep
Fuel and
water tanks
Instrument
bunker
C5
Fire pan
C4
C1
50 m radius
Cables buried
30 cm deep
C3
C7
150 m radius
Cables buried
10 cm deep
Liquid and vapour
drain lines
C6
C# designates camera shelter

Figure 2: Basic test site layout

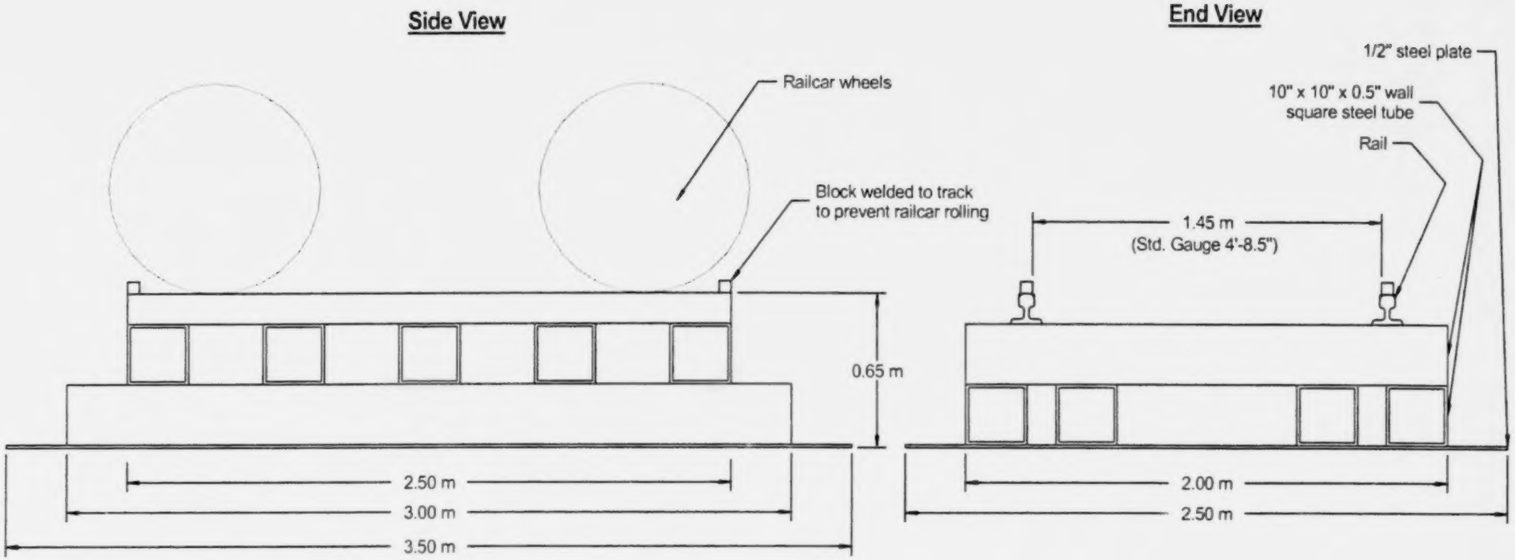

Side View
Railcar wheels
Block welded to track to prevent railcar rolling
0.65 m
2.50 m
3.00 m
3.50 m
End View
1/2" steel plate
10" x 10" x 0.5" wall square steel tube
Rail
1.45 m (Std. Gauge 4'-8.5")
2.00 m
2.50 m

Figure 3: Support of rail tank-car in fire pan

2.3. Tank-Car Modifications

The tank-car has to be modified to allow instrumentation wiring to exit it, and for remote vent and drain connections. Structures will also be required inside the tank-car, to support the lading thermocouples. The supports will be discussed in the tank-car instrumentation section. This section describes the additional access points, beyond the standard, into the tank-car. The modifications will have to be designed and installed by a qualified shop to ensure they comply with the appropriate section of the Association of American Railroads (AAR) M-1002- Specifications for Tank Cars. The objective of this section is not to provide access points designed to code, but to provide the required number and type of fittings, and a preferred layout. Changes to the layout, to meet code, must be made while considering the effect on the installation of the feed throughs and the placement within the instrument well.

2.3.1. Instrumentation Feed Throughs

All of the wiring inside the tank-car is clad in stainless steel. This allows it to pass through compression fittings screwed in to the tank-car producing a pressure tight seal. The majority of these cables are for the lading thermocouples, but a camera inside the tank-car requires two cables. Openings into the tank-car are also required to connect the pressure transducers. The pressure transducers connect to stainless steel tube that connects to a compression fitting in the tank-car wall, which opens into the tank-car lading. This allows the transducers to be located beneath the fire pan in a relatively cool location.

The vapour space pressure transducer requires an additional compression fitting on the inside of the tank, to attach a length of tube that terminates in the vapour space near the PRV. The required fittings are summarised in Table 2. Each of these fittings requires a half-coupling welded to the tank, which it will be screwed into. Figure 4 shows the locations of the half couplings on the tank. The wall area where the fittings and feed throughs are located has the insulation and jacket removed, but is within the instrument well and is fully thermally protected from direct impingement by the pool fire. Figure 4 also shows the half couplings for the drain connections.

Table 2: Fittings to allow instrumentation to enter tank-car

Sensor	Connections Required	Pipe Size (NPT)	Connections per Fitting	Part Number	No. of Fittings
Thermocouple Probes	21	¾ inch	3	Omega MFT-14-3	7
Pressure	2	¼ inch	1	Swagelok SS-1-400-1-4	3*
Transient Pressure	1	¾ inch	1	Drilled and tapped plug	1
Video Camera	2	¾ inch	3	Omega MFT-14-3	1
Total	**26**				**11**

* One pressure connection requires an additional fitting on the inside of the tank-car

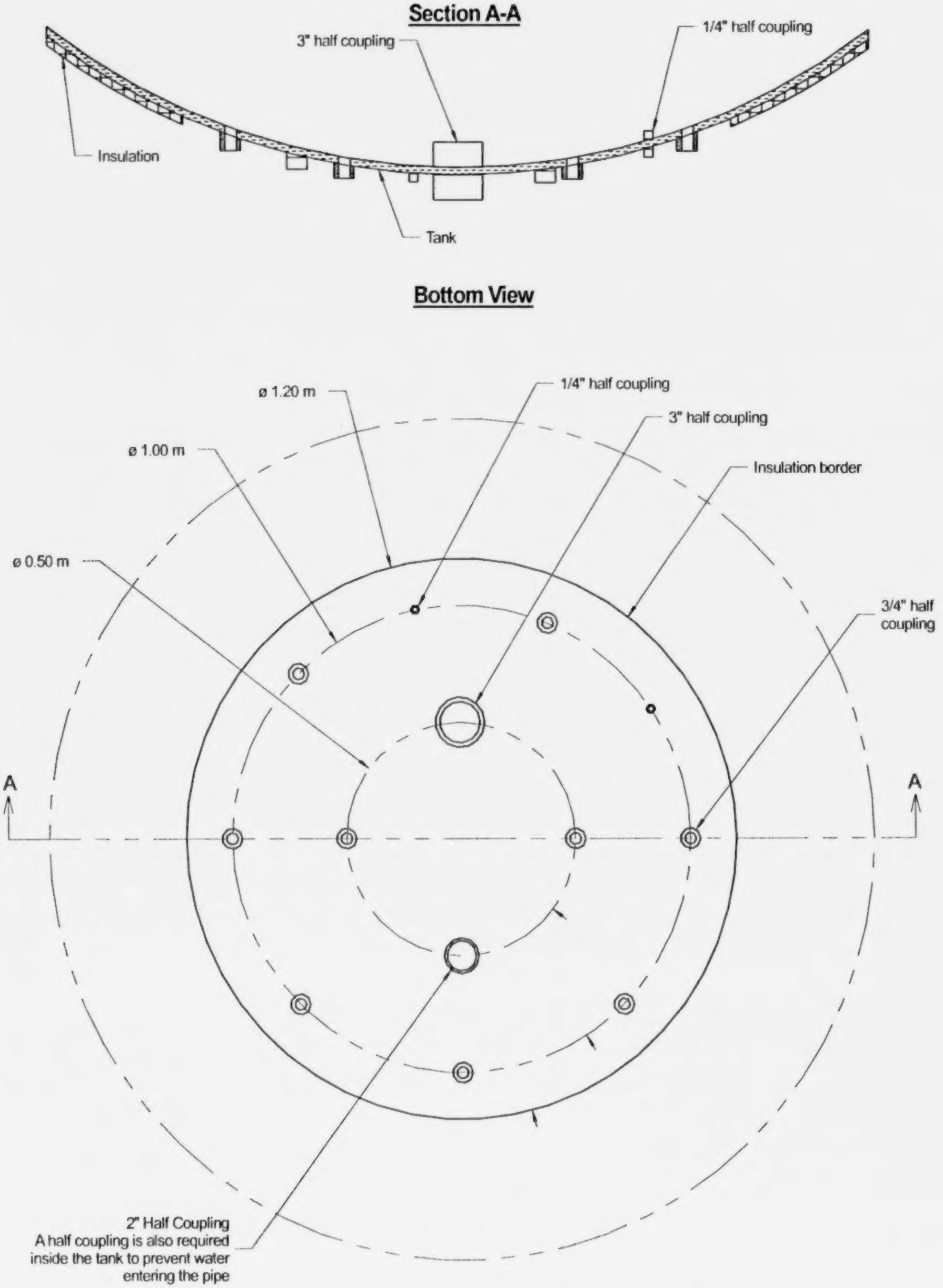

Section A-A
3" half coupling
1/4" half coupling
Insulation
Tank
Bottom View
ø 1.20 m
1/4" half coupling
3" half coupling
ø 1.00 m
Insulation border
ø 0.50 m
3/4" half coupling
A
A
2" Half Coupling
A half coupling is also required inside the tank to prevent water entering the pipe

Figure 4: Tank-car modifications for instrumentation and drain connections

2.3.2. Tank-Car Vent and Drain System

At the conclusion of the test it will be necessary to depressurise and drain, the possibly damaged, tank-car. The contents could either be vented and burned, or the propane transferred to another tank. The vent and burn capability would also act as a test abort system.

To achieve this, piping will be connected to the vapour space (top) and liquid space (bottom) of the tank-car. A 5.1 cm (2 inch) pipe provides the liquid drain and is connected to the bottom of the tank-car. A 7.6 cm (3 inch) pipe entering at the bottom of the tank-car, but piped internally to the vapour space, provides the vapour discharge for depressurisation. The 5.1 cm (2 inch) liquid drain requires a half coupling on the inside of the tank-car to prevent water at the bottom of the tank-car from draining into the pipe. When the tank-car is depressurised at the end of the test any water will freeze, due to the -42°C saturation temperature of propane at atmospheric pressure. If water accumulated in the pipe it could partially, or completely, block the flow when it freezes.

The drain tubes exhaust in the positions shown in Figure 2. Both pipes run through the instrument well, which is insulated, protecting them from direct impingement by the pool fire. They are then buried under the fire pan and remain covered by at least 10 cm of earth until a minimum of 25 m away from the fire pan. After that they are covered with at least 2 cm of earth, to reduce boiling in the pipes which could disrupt the pressure readings at the discharge point.

The liquid drain will empty into a shallow pit to contain the liquid propane until the burning area equalises the mass flow in and the burn-off rate. The vapour discharge will vent upwards. Each requires a pilot flame, to initially ignite the propane, supplied by a small burner attached to a propane cylinder. The pilot will be ignited prior to the test. Testing is needed to determine the size of pilot flame required, its position and propane requirement. A utility burner may be needed, which will require additional controls for the fuel and ignition. The objective of the pilot flame system is to keep the controls as simple as possible, while ensuring ignition of the venting propane.

The control valves for the drain system will be located approximately 10 m back from the exhaust, covered with a steel box, and buried under 30 cm of earth, to shield the thermal radiation from the pool fire and, to a lesser extent, from the propane flares. Pressure transducers will also be placed inside this box.

After the test has concluded the tank-car will be depressurised via the vapour discharge line. If the tank contents are to be burned off then the tank would be depressurised all the way down to atmospheric pressure. If the liquid contents are to be transferred to another tank then the venting process would be modified. A detailed transfer scheme has not been designed here. However, the value of the remaining propane may be substantial and warrant the cost of a transfer system.

Table 3 shows estimates of vent time for different scenarios and Table 4 shows drain times. The maximum vent time is 160 minutes (2.7 hours), for a tank starting at ambient temperature. This leaves 40.850 kg of propane which then take 6.2 hours to drain for a total time of 9 hours. Details of the estimation methods, and further results, can be found in Appendix C.

Table 3: Time to vent tank-car to within 1kPa of atmospheric pressure

Fill Level (Fraction liquid by volume)	Initial Temperature (°C)	Discharge Coefficient	**Time to Vent (Minutes)**
0.5	58	0.6	**73**
1.0	58	0.6	**128**
0.95	20	0.6	**160**
0.5	58	1.0	**43**

Table 4: Time to drain liquid propane from tank-car at atmospheric pressure

Pipe Diameter (cm)	Initial Propane Mass (kg)	Minor Loss Coefficient	**Time to Drain (Hours)**
5.1	20,500	3.4	**4.1**
5.1	20,500	6.8	**4.4**
5.1	40,850	3.4	**6.2**
7.6	20,500	3.1	**1.5**

2.4. Bunkers

Bunkers are required to protect equipment and personnel during the test and in the case of a tank-car failure. Three main bunkers are required:

1. Instrument bunker at 50 m radius.
2. Control bunker at 1000 m radius.
3. Visitor bunker at 2000 m radius.

In addition, camera shelters and fuel tank protection is required and are discussed in the relevant sections of this report.

2.4.1. Instrument Bunker

The instrument bunker is closest to the test and contains the data acquisition and control equipment. No personnel will be present in this location during the test. It must withstand the thermal radiation from the pool fire, and the blast and fireball if a tank-car fails. It must also remain cool enough during the test to allow the equipment to continue to operate. The best form of protection is to bury the bunker. This shields it from both thermal, blast and projectile hazards. The bunker itself will be a steel construction site office or storage container. A standard 8 foot wide x 8.5 foot high by 15 foot long container will suffice. An air conditioner, to remove the heat generated by the electronic equipment, and a ventilation opening, to allow airflow when personnel are present, must be installed. The cold junction temperature on the data acquisition boards will be recorded to monitor the temperature inside the bunker. This will be examined after the pre-test burns to ensure that it will not overheat over the duration of the full test.

A small berm will be built in front of the bunker to shadow it from any blast. Part of the rear wall will be exposed, to allow the installation of the air conditioner and ventilation opening. A steel plate will extend beyond the rear of the bunker to shield the exposed wall from the pool fire and any blast damage. In the case of a tank-car failure the bunker will be engulfed in the fireball and the air conditioner may not survive.

The ventilation will consist of steel hatches that can be opened when personnel are present and closed for the test. The door will also be kept partly open when personnel are present. The entrance will be accessed down stairs installed in an excavation. This entrance will be covered with a steel plate and 10 cm of earth during the test. Figure 5 shows the bunker with the access stairs and rear shield. All entrances will have to be raised above the surrounding grade to allow water to drain away. Depending on the test site conditions a sump pump may have to be installed.

2.4.2. Control and Visitor Bunkers

The control and visitor bunkers are far enough from the test site that the most likely hazard is broken glass. Steel construction site offices, suitably protected, will be used if bunkers are not available on the site. Both will be standard 8 foot wide x 8.5 foot high by 20 foot long containers.

The control bunker at 1000 m will have small windows on the side facing the tank-car, to allow observation and photographing of the test. The windows will be made of plastic to prevent breakage. This bunker should be hardened to protect against possible projectiles. This will require concrete block walls sufficient to take a strike from a large tank fragment travelling at speeds up to 50 m/s. Blast and fire damage at this distance should not be significant. The door will be on the side of the container facing away from the test. For the comfort of the test personnel this bunker should be air conditioned. Personnel required to stay in this bunker will be issued with hearing protection.

The visitor bunker at 2 km is very unlikely to be exposed to any hazards. However, there is a very small chance a projectile could reach this distance so some hardening would be desirable. Further details of this bunker will be worked out when the number of observers is established.

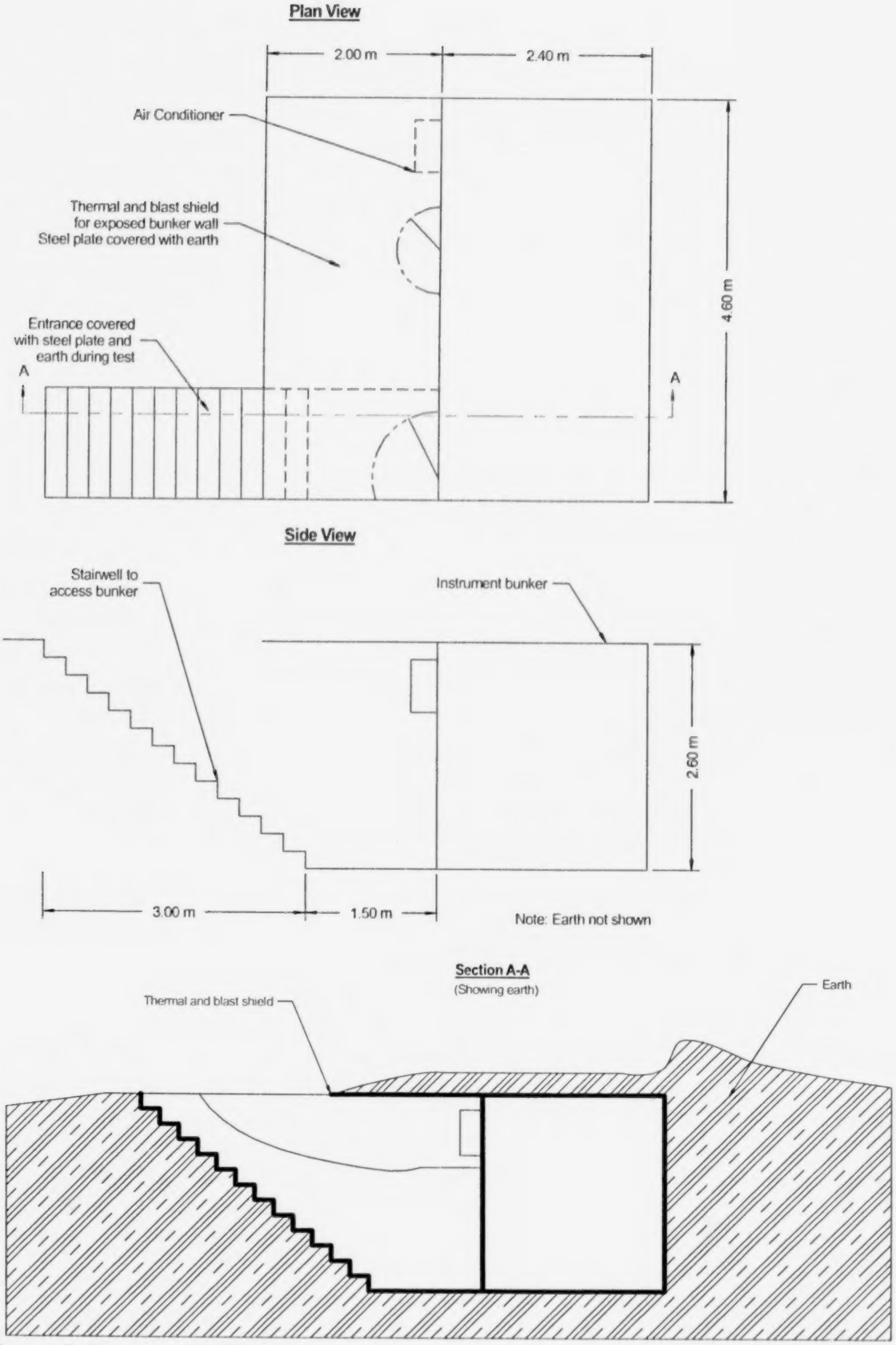

Plan View
2.00 m
2.40 m
Air Conditioner
Thermal and blast shield for exposed bunker wall Steel plate covered with earth
Entrance covered with steel plate and earth during test
A
A
4.60 m
Side View
Stairwell to access bunker
Instrument bunker
2.60 m
3.00 m
1.50 m
Note: Earth not shown
Section A-A
(Showing earth)
Thermal and blast shield
Earth

Figure 5: Instrument bunker

3. Test Procedures and Safety

Test procedures are required to ensure that the tests are carried out safely, that each test is performed under the same conditions, all data is recorded, and the control systems work properly. The procedures presented here are intended as a work in progress. They will require modification and refinement as the final details of the test itself are defined. These procedures are based on the design details in this report and any modifications to them may require updates to these procedures. All procedures must be reviewed and updated once the test site has been prepared.

3.1. Tank Fill Procedure

Once the tank has been inspected and all tank preparations are completed, it will be filled. The following basic steps are needed for filling:

1. Clear all unnecessary personnel from tank location.
2. Open manual vapour vent valve and close manual liquid drain valve.
3. Turn on data acquisition system to monitor pressure and temperatures during leak test and fill.
4. Conduct leak tests on all fittings by pressurizing tank with 200 kPaG (29 PSIG) air (large air compressor needed).
5. Fix all leaks.
6. Vent tank to ambient pressure using vapour vent line.
7. Purge and fill tank (details in section 3.2).
8. Confirm purge and fill based on measured data.
9. Close all manual valves on vapour and liquid lines.
10. Secure the site.

At this point the tank is ready for a test. Unnecessary personnel should not be allowed near the tank. Monitors for gas leaks should be used to ensure the site is safe.

3.2. Purge Procedure

The tanks will arrive full of air. The tank interiors will be inspected to ensure that all instruments are still intact. Once the tank is ready to fill the air must be purged and replaced with propane vapour. This is a critical detail and must be performed properly. Proper purging of the tank can take considerable effort and time. If the air is not purged, the PRV will open prematurely during the test and introducing an error that is difficult to correct. We will not know if the propane or the air popped the PRV. We need to know this if we want our computer models to be accurate.

Purging in all propane vessels prevents the compression of the air from over pressurising the tank as the vessel fills with liquid. Figure 6 shows the pressure in the tank, using the ideal gas isothermal compression assumption, after filling a rail tank-car 95% with liquid propane. 150 kg represents the mass of air in the tank if no purging is done. In reality the PRV will open at about 1.9 MPaG (280 PSIG), limiting the tank pressure, but resulting in non-desirable behaviour.

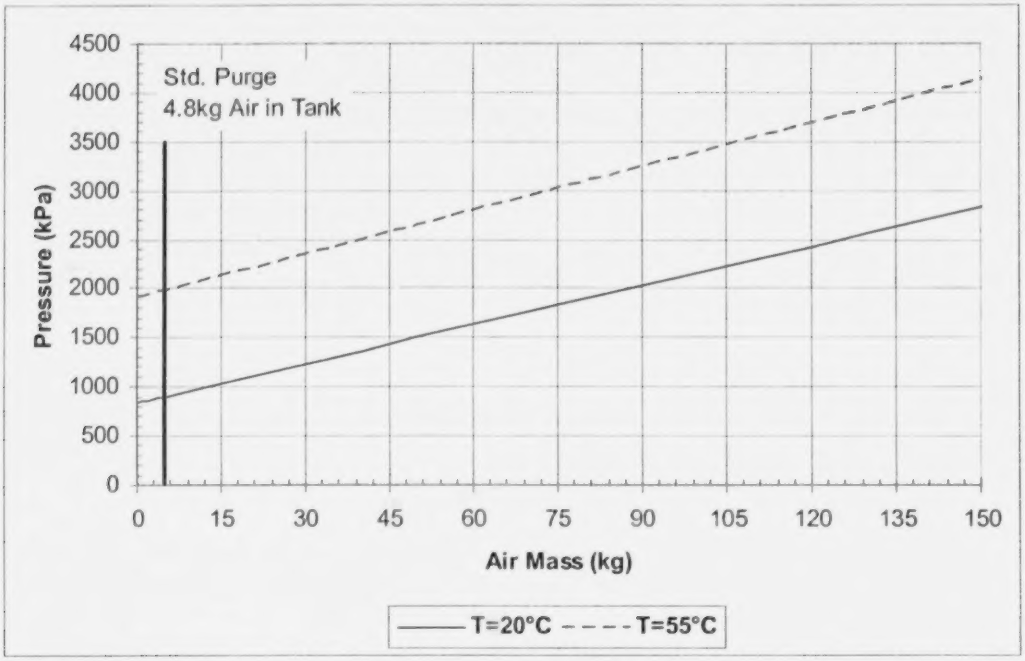


Figure 6: Pressure in a 127 m^3, 95% full, propane rail tank-car with mass of air left in the tank-car

The standard purge procedure, according to the Ontario Propane Association, involves pressurising the tank with propane vapour to 2 atmospheres absolute, venting and repeating 5 times (2006). This requires 1170 kg of propane for a 127 m^3 tank-car. The mass of air remaining in the tank-car is 4.8 kg which is 3.1% (Fraction_{air}=0.03125) of the gas in the tank-car prior to filling. The ability to supply this amount of propane vapour in the field will be limited, unless evaporators are used.

Instead, liquid propane could be pumped into the tank-car, which performs as an evaporator, while being vented to atmosphere. The vaporising propane displaces the air in the tank-car. Unfortunately the thermally protected tank-car has a low heat transfer rate. If 1170 kg of liquid propane was added to a tank-car, after 24 hours it would have about 32 kg of air (Fraction_{air}=0.21) and approximately 550 kg of liquid propane remaining.

Another option is to vent the tank-car as it is being filled. When the tank-car pressure exceeds the saturation pressure of the liquid by a pre-set amount the tank-car is vented to atmosphere through the vapour vent line. This introduces uncertainty in the mass of propane in the tank-car, but modeling indicates that the propane mass would be reduced by approximately 1%. This is the recommended technique. The purge/fill procedure is as follows. This is part of the fill procedure given in section 3.1.

1. Ensure all outlets on tank-car are closed (manual and automatic liquid drain valves closed, automatic vapour vent valve closed, but manual vapour vent valve open).
2. Fill tank-car with liquid propane.
3. As tank-car fills, when pressure exceeds liquid saturation pressure by 700 kPa (100 PSI) open vapour release valve until pressure exceeds saturation by less than 350 kPa (50 PSI) and then close valve.
4. When the tank-car is 95% full open vapour release valve until pressure in tank-car exceeds saturation by less than 35 kPa (5 PSI) and then close valve.

If the ambient temperature is 20°C, the inlet flow rate is 3.8 L/s (60 gallons/minute) and the valve requires one second to close after the close pressure is reached, the final condition will be as follows:

$\text{Fraction}_{air}=0.026$
Mass of air left in tank-car=3.9 kg
Mass of propane vented=600 kg

The procedure above assumed a measuring device to indicate when the tank-car was 95% full, if such a device was not available and the fill based on the amount of propane added it would be approximately 94% full. Varying the fill rate had a negligible effect on the modeled results. The ambient temperature and the pressure above saturation to vent the tank-car, did affect the amount of propane discharged and the remaining fraction of air.

During this procedure care must be taken to ensure that liquid is not vented from the tank. This means we must be careful about levelling of the tank and the location of the vapour vent line intake.

The ambient temperature of the air and propane has an effect on the quantity of propane vented and air remaining after the fill procedure, as shown in Table 5. The majority of the difference is due to the higher saturation temperature of the warmer liquid. Both the air remaining and propane vented increase with temperature. The worst case examined was 35°C, which had a $\text{Fraction}_{air}=0.031$ and vented 1.4% of the final propane mass in the tank-car. This is the same as fraction of air remaining after the standard purge.

Table 5: Effect of temperature on propane vented and air remaining after purge procedure

Temperature (°C)	Propane Vented		Air Remaining	
	Mass (kg)	Fraction	Mass (kg)	Fraction
-10	266	0.004	3.3	0.021
0	355	0.006	3.4	0.022
10	465	0.008	3.6	0.024
20	600	0.010	3.9	0.026
30	756	0.013	4.4	0.029
35	850	0.014	4.7	0.031

The simulated pressure and fill rates, in the tank, during the fill, are given in Appendix D. The final tank pressure, pressure above saturation to start venting, vent line discharge coefficient and fill rate also effect the propane vented and air remaining, to varying extents. These effects are examined in Appendix D.

3.3. Start and Operating Procedure

During the test start procedure, checklists must be used to ensure critical steps have been performed and to provide a record of the test. The following procedure prepares the test apparatus and ensures the safety of test personnel. It lists the activities required immediately prior to and during the test. It assumes all manual valves are closed and that the test apparatus is correctly installed and prepared prior to initiating the procedure.

There will be four operators controlling the test as follows:

i) site engineer
ii) data acquisition engineer
iii) instrumentation and control engineer
iv) photo/video engineer

There will be four individuals (safety officer, site engineer, instrumentation and control engineer, camera operator) remaining at or near tank location during the final checklists. They will be evacuated to the control bunker before the test begins.

Each of the operators will have specific checklists to complete. There will be several checklists as follows:

i) general
ii) fire ignition systems
iii) fuel delivery systems
iv) general data acquisition and control
v) high-speed data acquisition system
vi) computer networks
vii) vent and drain systems
viii) cameras

The following lists are provided for consideration. Additional details will be required as the test design is finalized.

3.3.1. General Test Checklist

1. Test safety briefing is conducted to ensure that everyone knows what is about to happen. This may include local fire department and health officials.
2. Review forest fire or grass fire status.
3. Remove all personnel not involved in the final test preparation to the visitor or control bunkers.
4. Test director verifies test site is clear of unauthorised personnel and no fly zone is in place.
5. Radio checks are done to ensure the site is secure.
6. Phone calls are made to anyone needing a warning about what is about to happen.

7. Test director ensures all personnel are accounted for.
8. Final check of fuel delivery system.
9. Final check of fire ignition system.
10. Final check of vent and drain systems.
11. Final check of data acquisition systems.
12. Final check of power systems.
13. Final check of camera systems.
14. Final check on weather conditions (wind speed, direction, cloud cover, etc).
15. Obtain final go ahead from Director and range safety officer.
16. Start recording data.
17. Test director ensures data is being recorded and gives go ahead to begin test.
18. Fill fire pan with fuel.
19. Light all pilot flames and flares.
20. Turn on cameras.
21. Evacuate crew from test site to control bunker (1000 m).
22. Final check on personnel.
23. Activate ignition burners.
24. Activate high-speed data acquisition.
25. Once burners are going deactivate igniters.
26. Once pool fire is burning activate automatic fuel control system.
27. Leave ignition burner fuel valves open.
28. Monitor test conditions.
29. Monitor the abort status.
30. When test ends follow appropriate shutdown procedure.

The following sections give additional details for each final check.

3.3.2. Final Check Fuel Delivery

1. Verify power system is on.
2. Verify operation of fuel supply valve.
3. Verify valves controlling liquid fuel are set to allow fuel to be pumped to fire pan.
4. Verify fuel level control system is set.
5. Check fuel level meter is reading correctly and adjust if necessary.
6. Verify remote manual control is operational.
7. Open manual fuel supply valve.

3.3.3. Final Check Fire Ignition

1. Enable spark ignition system.
2. Activate 120V operating power supply and confirm operation.
3. Activate control system power supply and confirm operation.
4. Verify operation of spark igniters.
5. Verify operation of propane ignition burner valves.
6. Verify remote control is operational.

3.3.4. Vent and Drain Systems

1. Verify operation of vapour discharge valve.

2. Verify operation of liquid drain valve.
3. Verify remote manual control of vapour and liquid lines.
4. Ignite vapour and liquid discharge pilot burners.
5. Verify remote vapour and liquid drain valves are closed.
6. Open vapour discharge manual valve.
7. Open liquid drain manual valve.

3.3.5. Final Check General Data Acquisition

1. Turn DAC system on at least 60 minutes prior to test.
2. Check hard disk has adequate free space for data.
3. Verify data acquisition system is measuring data.
4. Turn on power for calorimeter pumps.
5. Verify calorimeter pumps operate.

3.3.6. High-speed Data Acquisition

1. Turn on high-speed data acquisition power supplies.
2. Turn on high-speed video system.
3. Turn on high-speed data capture systems and confirm operation.
4. Turn off all lights, computer monitors and other peripherals in instrument bunker. Leave on only equipment required during test.
5. Confirm air conditioner is operating.
6. Close instrument bunker and cover stairwell.

3.3.7. Computer Networks

1. Verify control bunker is connected to data acquisition computers in instrument bunker by wireless communication.
2. Verify control bunker can view and control webcams.
3. Verify visitor bunker can view web cam and data acquisition computers.

3.3.8. Cameras

1. Check camera positions and settings.
2. Confirm cameras are on and ready.
3. Start video cameras when given signal.

3.3.9. Weather

1. Check wind speed and direction.
2. Check pressure and wind speed trend.
3. Communicate to test director.

3.3.10. Pre-test Checklists

The following checklists should be filled out during the start procedures to ensure everything is prepared to test and all personnel are safe. They form part of the test record and will be used to help trouble shoot the test if the need arises.

3.3.10.1. Video and SLR Camera List

The following list is repeated for each camera by the photo/video engineer.

Item	Checked
SLR Cameras	
Camera is on	
Remote control system is connected	
Film is in camera and unused	
Camera is set to record date and time	
Camera is set in continuous picture taking mode	
Field of view is correctly aimed and zoomed	
Camera is focused	
Exposure is set	
Camera is in manual focus mode	
Video Cameras	
Camera is on and in camera mode	
Hard drive is empty	
Camera is set to record date and time	
Field of view is correctly aimed and zoomed	
Camera is focused	
Exposure is set	
Camera is in manual focus mode	
Camera is recording	

3.3.10.2. Fire System Checklist

Before proceeding to the Data Acquisition and Control Checklist complete the following checklist.

Item	Checked
Manual vapour discharge valve is closed	
Manual liquid drain valve is closed	
Manual fuel supply valve is closed	
No fuel is in fire pan	
No fuel is in ignition system	
Toggle switch in spark ignition power line is open (i.e. Off)	
Computer control of fuel pump is set to OFF	
Fire pan has required water fill level	

3.3.10.3. Data Acquisition and Control Checklist

This checklist should be completed in conjunction with the start/operating procedure

Item	Checked
Data Acquisition	
DA system is on and measuring data	
Hard drive has enough free space to record test	
Control bunker is connected to instrument bunker computer	
Control and Power Systems	
12V control power supply is on	
120V operating power supply is on	
Spark igniters operate	
Vapour discharge valve opens and closes (from control bunker)	
Vapour discharge valve is closed	
Liquid drain valve opens and closes (from control bunker)	
Liquid drain valve is closed	
Manual liquid drain valve is open	
Manual vapour vent valve is open	
Fuel and ignition systems	
Ignition system is fuelled and set up	
Fuel supply valve opens and closes (from computer)	
Toggle switch in spark ignition power line is closed	
Spark igniter works	
Turn on manual power switch for fuel pump	
Manual fuel supply valve is open	
Initial quantity of fuel is in fire pan	

3.3.10.4. Final Checklist

Immediately prior to energizing the igniters the test director will complete the following list.

Item	Checked
Video and SLR camera checklist is completed	
Data acquisition and control checklist is completed	
Confirm no fly status for test area	
Confirm test area is secured from unauthorised entry	
Wind speed and direction are acceptable	
Data is being recorded	
All personnel are accounted for in control or visitor bunker	

3.4. Abort and Shutdown Procedures

The abort and shutdown procedures presented here are based on the design and modeling criteria set out in this report. Figure 7 is a decision tree to determine the correct procedure to follow. Procedures may require modification based on conditions during the abort. The procedures are meant to provide guidance, but not all scenarios can be foreseen. If a problem occurs early in the test, prior to opening of the PRV and before wall temperatures reach 300°C the test should be aborted without removing propane from the tank-car, so it can be allowed to cool and the test restarted.

If there is some unforeseen scenario where the test needs to be shut down then the following procedure should be followed.

1. Turn off the pool fire fuel if possible.
2. Let the pool fire burn out.
3. Keep taking data if possible.
4. Assess if the tank contents should be vented.
5. Follow the safe cool down procedure.

The test is set to run with two separate computer systems. One is for data acquisition and one is for data acquisition and control. If the data acquisition computer fails the test can be continued with the second, data acquisition and control, computer. If the data acquisition and control computer fails it may be possible to continue the test under manual control, acquiring data from the data acquisition computer.

3.4.1. Procedure A: Test time concluded and no failure occurred

1. Shut down pool fire fuel supply (turn off pump and close valve) and allow fire to burn out.
2. Open vapour discharge line and vent pressure from tank.
3. When tank-car pressure is close to atmospheric, open liquid drain valve and burn-off liquid.
4. When pool fire is out, turn off calorimeter pumps.
5. Continue recording data until the following criteria are met:
    a. Pool fire is out.
    b. Vapour discharge line is open and tank pressure is near atmospheric.
    c. Maximum temperature reading is less than 300°C.
6. Back up all data to control computer in control bunker and portable media.
7. Follow safe cool down procedure before approaching tank.

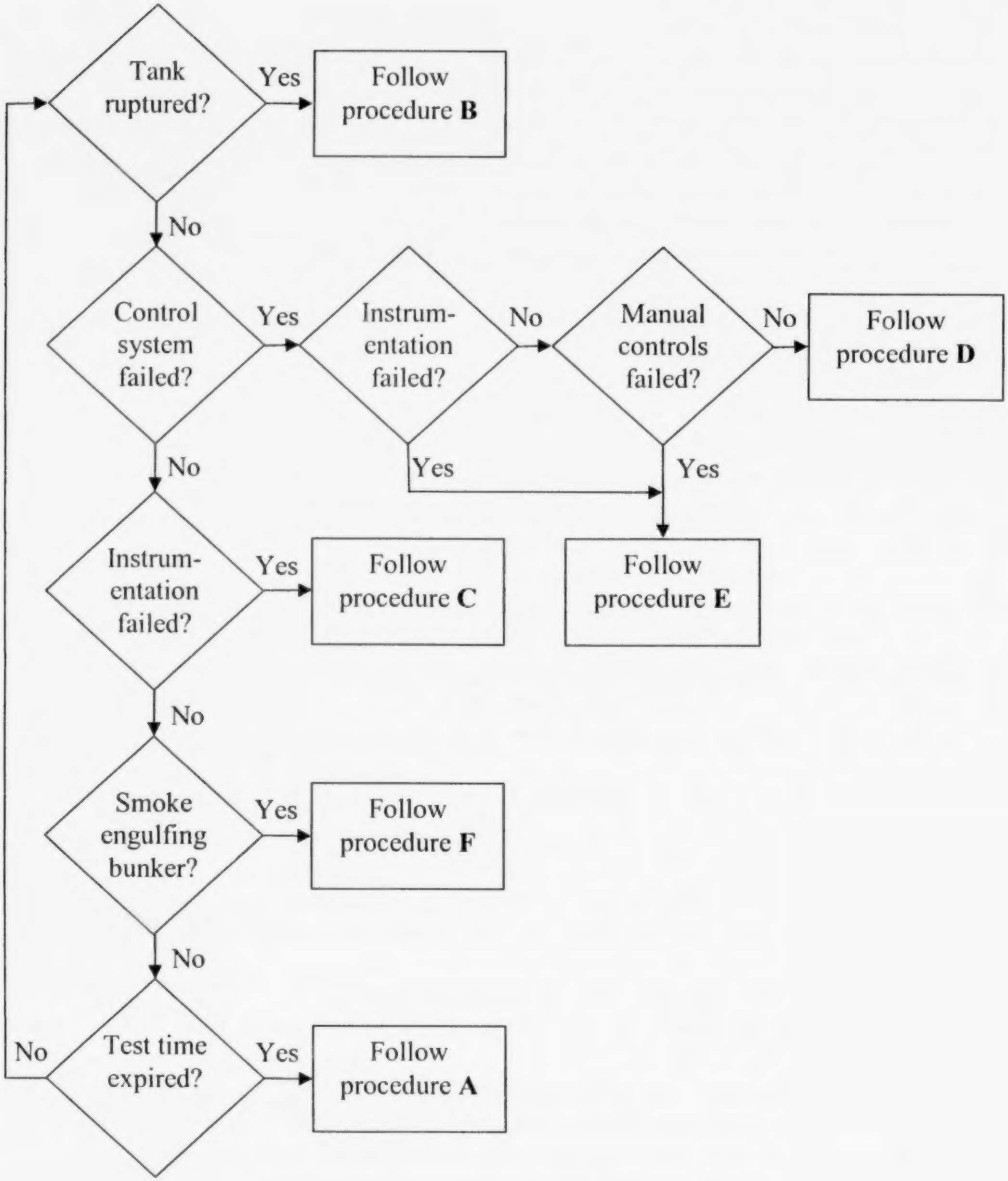

Tank ruptured?
Yes
Follow procedure **B**
No
Control system failed?
Yes
Instrum-entation failed?
No
Manual controls failed?
No
Follow procedure **D**
Yes
Yes
No
Instrum-entation failed?
Yes
Follow procedure **C**
Follow procedure **E**
No
Smoke engulfing bunker?
Yes
Follow procedure **F**
No
No
Test time expired?
Yes
Follow procedure **A**

Figure 7: Test abort and shutdown procedure decision tree

3.4.2. Procedure B: Tank-car ruptures

1. Shut down pool fire fuel supply (turn off pump and close valve).
2. Back up all data to control computer in control bunker and portable media.
3. Shut down calorimeter pumps.
4. Let fire burn out.
5. If tank-car is intact and vapour is venting, then open liquid drain valve once pressure reaches atmospheric in tank.
6. Follow safe cool down procedure before approaching tank.

3.4.3. Procedure C: Instrumentation failure

1. Is data acquisition and control computer still functioning? (i.e. has only the data acquisition computer failed?) If yes, continue test, otherwise continue this procedure.
2. Shut down pool fire fuel supply (turn off pump and close valve).
3. Back up all data to control computer in control bunker and portable media.
4. If PRV valve has not opened and wall temperatures were all below 300°C, wait 24 hours, confirm the tank is safe to approach and then approach tank-car to prepare for re-test.
5. Otherwise (i.e. tank is not safe for re-test), open vapour discharge line to vent pressure.
6. When tank pressure is near atmospheric, open liquid drain line to burn of remaining liquid.
7. Follow safe cool down procedure before approaching tank.

3.4.4. Procedure D: Control system failure but instrumentation readings still available

1. Loss of control system should close pool fire fuel supply and open vapour release valve.
2. Is data acquisition only computer still functioning? If yes, can test be controlled manually (can fuel levels be monitored)? If yes, close vapour valve and continue test using manual controls. If not, continue procedure.
3. If the actions in step 1 do not occur, use the manual override switches as follows:
    a. Shut down pool fire fuel supply (turn off pump and close valve).
    b. If PRV valve has not opened and wall temperatures were all below 300°C, wait 24 hours and then approach tank-car to prepare for retest.
    c. Otherwise open vapour discharge line.
4. If manual override switches do not work, shutdown all electrical power to the test site and follow failure of control system and instrumentation procedure.
5. When tank-car pressure is close to atmospheric open liquid drain valve.
6. Continue recording data until the following criteria are met:
    a. Pool fire is out.
    b. Vapour discharge line is open and pressure has dropped and tank pressure is near atmospheric.

   c. Maximum temperature reading is less than 300°C.
7. Back up all data to control computer in control bunker and portable media.
8. Follow safe cool down procedure before approaching tank.

3.4.5. Procedure E: Control system and instrumentation failure

1. Loss of control system should close pool fire fuel supply and open vapour release valve.
2. If the above actions do not occur, the problem may be with computer in the control bunker. If test appears to be functioning correctly, reboot computer and attempt to reconnect to instrument bunker computer. If successful continue test.
3. If the fuel supply does not close or vapour valve does not open, use the manual override switches and then follow Procedure C.
4. If the manual override switches do not work (or you are unsure if they are working), shutdown all electrical power to test site and then follow Procedure C.
5. If unsure that vapour and liquid drain valves opened, wait 24 hours before approaching tank-car and manually activate valves as follows:
   a. Open vapour discharge – leave test site and wait 3 hours.
   b. Open liquid drain – leave test site and wait 7 hours.
   c. Follow safe cool down procedure.

3.4.6. Procedure F: Control bunker is engulfed in smoke from pool fire

1. Shut down pool fire fuel supply (turn off pump and close valve).
2. If PRV valve has opened or wall temperatures exceeded 300°C, open vapour discharge line.
3. Leave bunker and move to visitor bunker (continue recording data).
4. When pool fire has burnt out, return to control bunker.
5. If PRV valve has not opened and wall temperatures were all below 300°C, wait 24 hours and then approach tank-car to prepare for re-test, otherwise open vapour discharge line.
6. When tank-car pressure is close to atmospheric, open liquid drain valve.
7. Continue recording data until the following criteria are met:
   a. Pool fire is out.
   b. Vapour discharge line is open and pressure has dropped and tank pressure is near atmospheric.
   c. Maximum temperature reading is less than 300°C.
8. Back up all data to control computer in control bunker and portable media.
9. Follow safe cool down procedure before approaching tank.

3.4.7. Safe Cool-down Procedure

Once a test is terminated, the test site should be allowed to cool down. This could take several hours (see section 3.5.2). The test tank should not be approached until all of the following are true.

i. All fires are out.
ii. It is confirmed that the tank is empty of liquid and has zero pressure gauge.
iii. Systems have had time to cool down to below 200°C.

If fires continue, then firefighters may need to take action. They should not be allowed to approach within 1000 m of the tank until it is confirmed the tank is empty of liquid and there is no pressure in the tank.

3.5. Test Safety

It has been assumed that the test site will operate using standard practices for explosive test ranges. A dedicated range safety officer will be assigned. All details of the site safety plan will be developed after the site has been selected. The two main sources of hazard from the test program are a tank rupture and the pool fire. Remaining safety concerns are those common to other construction site activities.

A tank failure could result in a BLEVE. A BLEVE can produce a fireball, thermal radiation, blast overpressures and projectile hazards. The hazards could extend kilometres from the test site. The pool fire is more localised but of longer duration. The test will last for 100 minutes and the pool fire could require an additional 20 minutes to burn out. The thermal radiation and smoke produced by the pool fire are significant hazards, to both human health and equipment.

3.5.1. Hazards in the Event of Tank Rupture

Estimates of fireball size and duration, thermal radiation, blast overpressure and blast damage were performed using the calculations presented by BAM in their report on a European propane rail tank-car pool fire test (Balke et al., 1999) and are presented in Appendix E. Projectile hazards have been estimated using the methods proposed by Birk (1996). Appendix E also provides a comparison of the hazards in the previous 1900 L (500 gallon) tank test program and this proposed test series.

3.5.1.1. Vapour Cloud Explosion

The first assessment of the blast damage modeled the detonation as a vapour cloud explosion and assumed all the propane in the tank-car was involved. This is very unlikely. Table 6 provides a correlation of the blast measure, C, to damage inflicted on humans and buildings. Figure 8 shows the calculated blast strength with distance from the ruptured tank-car. The locations of the instrument bunker, fuel tank, control bunker and visitor bunker are also shown. This correlation places the visitor bunker in the no effect on humans and the control bunker in the temporary hearing damage. The instrument bunker is well within the total devastation range, and the fuel tanks border it and severe damage. Significant protection will be provided for both of these facilities. With this measure, for a full tank, the blast is not harmless until 4 kilometres away.

Table 6: Injuries and damage corresponding to blast measure C

Human Injury	Building Damage	C
None	Occasional breakage of glass panes	100 - 50
Temporary hearing damage	Breakage of glass panes	50 - 20
Falling down	Repairable damage to buildings	20 - 11
Burst eardrum	Severe damage to industrial buildings	11 - 5.5
Long term injuries to death	Total devastation	5.5 - 0.85

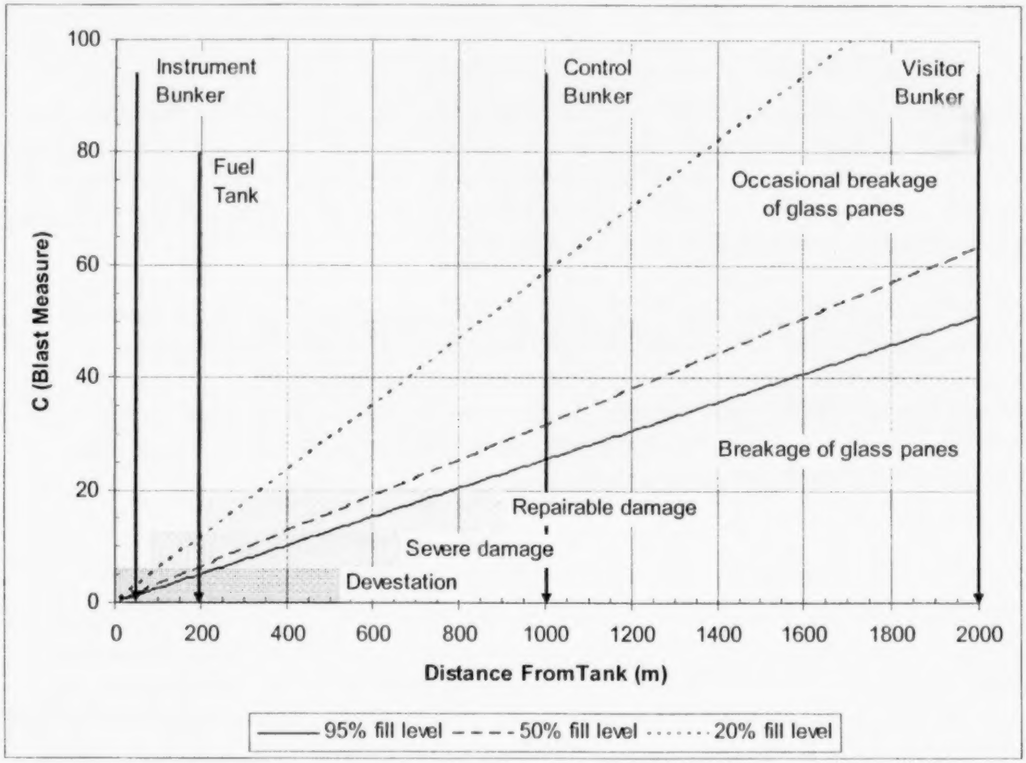


Figure 8: Blast measure with distance from tank-car

3.5.1.2. BLEVE Blast

Another source of blast damage comes for the expansion of the tank contents and uses the energy in the pressurised vapour to estimate the maximum overpressure of the blast wave. The effect of overpressures is given in Table 7. Figure 9 relates the blast overpressure to distance from the tank-car assuming that the tank-car was filled with propane vapour at 5600 kPa (812 PSIA). This pressure was chosen because it is the pressure used in the BAM calculations assuming no relief valve (i.e. the BAM test tank had no PRV). Since these tests will include a relief valve, the pressure will be less than the BAM tests, but this provides a conservative result. Figure 9 shows that the damage estimates for this technique are an order of magnitude lower than for the vapour cloud explosion. With this technique the blast is harmless at about 350 m.

Table 7: Injuries and damage corresponding to blast overpressure (Balke et al., 1999)

Building Damage	Δp (kPa)
Harmless	<2
Light damage to wooden and multi-storey stone buildings, breakage of windows	2 - 5
Light damage to roofs, metal and reinforced concrete structures and wooden bridges	5 – 10
Medium damage to brick buildings, metal constructions and wooden bridges	10 – 30
Total destruction to industrial buildings, pipe bridges etc.	40 - 80
Destruction of overhead power lines, concrete bridges and transformer stations	100 - 200

Note: Human deaths are possible for >70 kPa

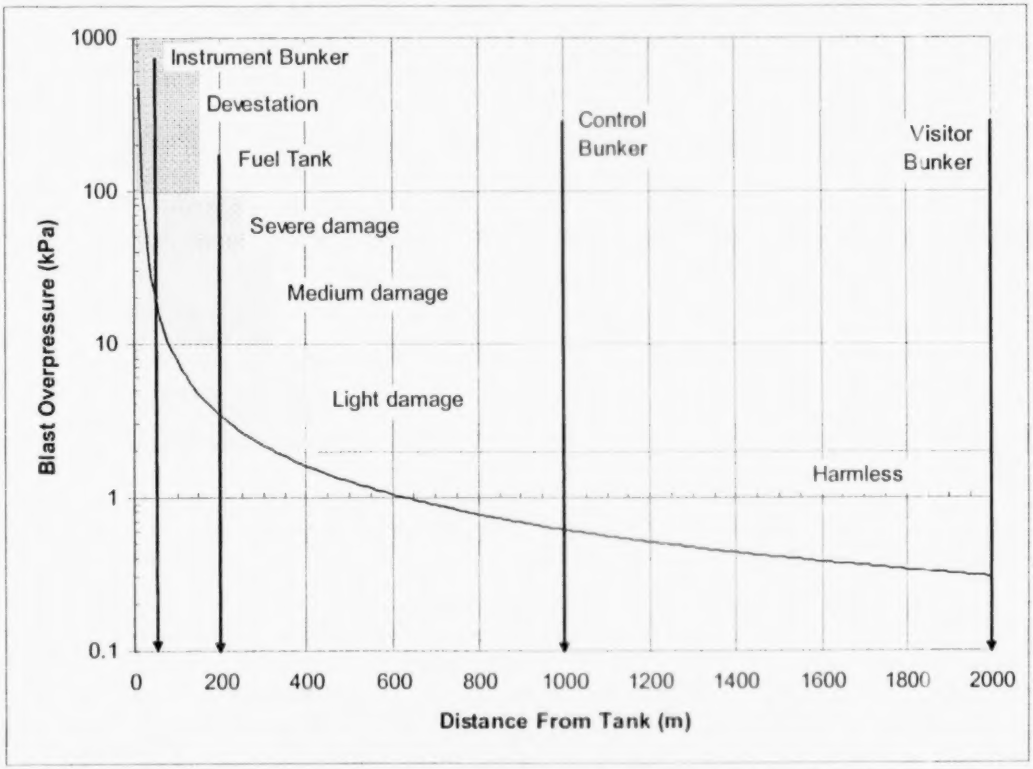


Figure 9: Blast overpressure (from expansion of tank contents) with distance from tank-car

3.5.1.3. *BLEVE Fireball*

Thermal radiation from the fireball is an additional hazard from ruptured propane tanks. This is created by the combustion of the propane remaining in the tank at failure. The most severe effect is to the area engulfed by the fireball, but locations beyond the fireball also receive a significant exposure to thermal radiation, especially when the duration is accounted for. Figure 10 shows the heat load with distance from the tank-car. The ignition limit of organic substances is also given. Based on that limit a firebreak should be created at a radius of 600 m.

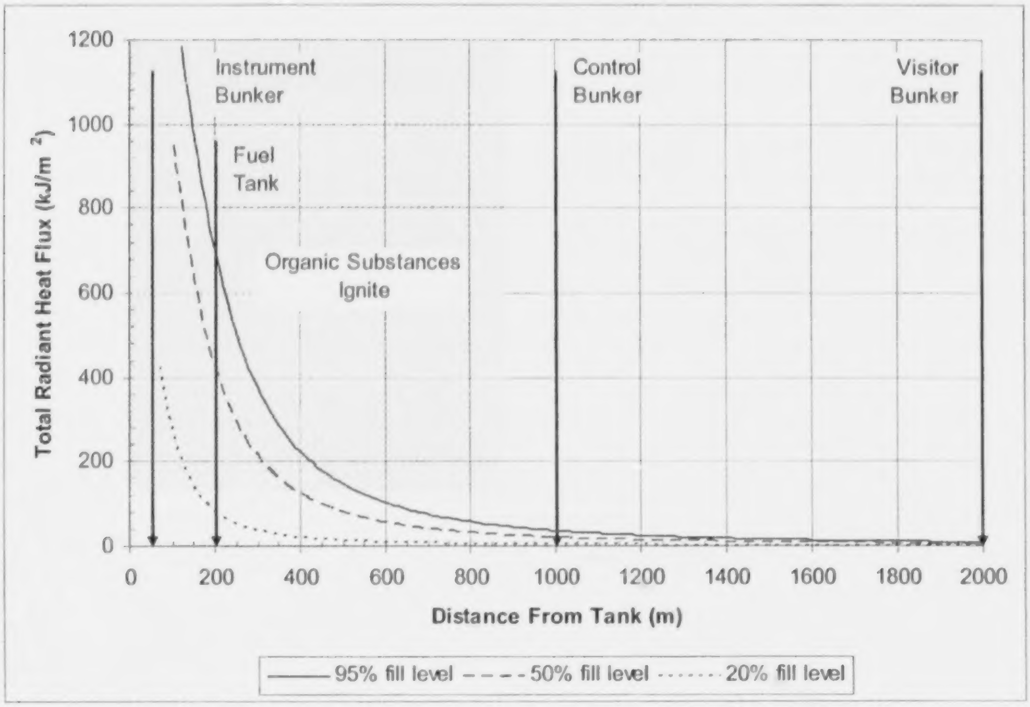


Figure 10: Thermal heat load from fireball with distance from tank-car

3.5.1.4. *Projectiles*

The worst kind of projectile is a tub rocket. In the Mexico City disaster a cylindrical tank, smaller than a rail tank-car, travelled 1200 m.

As a rule of thumb, tub rocket ranges for large tanks can reach 10-15 times the fireball radius. In this case this would translate to 900 to 1400 m for a rail tank-car filled to 50% at the time of failure. As an estimate for this size tank, 80% of projectiles are expected to fall within 200 m and 95% of projectiles should fall within 650 m.

3.5.2. Pool Fire

The pool fire produces a massive thermal load and a toxic mixture of combustion products and soot. This produces a huge black cloud that will rise into the air and drift downwind. For personnel the hazards can be avoided by remaining at a safe distance, upwind of the fire. The distances required to be safe in case of a BLEVE exceed the required distance to avoid the main hazards of the pool fire, except for the smoke cloud. Procedures must be in place to ensure the pool fire is not ignited while personnel remain in the vicinity. To ensure this the start procedure presented for the full test should also be followed for pre-test burns.

A change of atmospheric conditions could cause the control bunker to be engulfed in smoke from the pool fire and, although very unlikely, this could complicate the test procedure. One approach would be to provide respirators for the critical operators in the control bunker. Another approach would be to have redundant control in the visitor bunker so the operators could move there.

Equipment will have to be located near the pool fire. The simplest technique to protect equipment from the thermal load is to bury it. Modeling of ground heating was done to determine the depth required to protect the equipment. The details are given in Appendix F. The pool fire was assumed to burn for 120 minutes followed by a fireball engulfing the surface for 20 seconds. The chances of a fireball occurring are very low, but this was considered the worst possible scenario. The temperature profiles at three locations, engulfed by, adjacent to and at 50 m (the instrument bunker) from the pool fire, were modeled. Table 8 gives ground temperatures at the conclusion of the test and after an additional 20 second fireball engulfment. At 30 cm deep the temperature is unaffected by the heating and at 10 cm no effect of the fireball is felt.

The same properties that make the earth a good insulator, protecting cables and equipment, make it slow to cool down. Table 9 gives the time for the surface to reach 40°C after the test and fireball. The simulation used conservative cooling rates so the time should be a maximum. To ensure safety of personnel no one should approach closer than the instrument bunker until 10 hours after a full length test. The sub-surface temperatures continue to rise after the fire is extinguished as the heat near the surface is conducted down.

Applying a margin of safety all cables and instruments will be buried 30 cm deep out to the instrument bunker. From the instrument bunker out to 150 m the cables will be under 10 cm. To protect from thermal radiation from the fire ball, the cables will be under 2 cm out to 400 m and, as a precaution, be covered out to 600 m, where the firebreak is located.

Table 8: Modeled sand temperatures at surface, 10 cm and 30 cm deep after 120 minute pool fire and 20 second fireball

Location	Temperature at Test Conclusion (°C)			Temperature after Fireball at Test Conclusion (°C)		
	Surface	10 cm Deep	30 cm Deep	Surface	10 cm Deep	30 cm Deep
Engulfed	1015	57	20	1015	57	20
Adjacent	800	49	20	970	49	20
50 m	120	22	20	770	22	20

Table 9: Modeled time and temperatures below surface of sand when surface temperature has cooled to 40°C after 120 minute pool fire and 20 second fireball

Location	Time Since Test Conclusion (Hours)	Temperature 10 cm Deep (°C)	Temperature 30 cm Deep (°C)
Engulfed	17.6	70	33
Adjacent	15.1	67	29
50 m	2.2	32	20

4. Fire System

A large, engulfing, liquid hydrocarbon, pool fire, will be used to heat the tank-car. This is the same technique used in past full-scale tank-car testing by BAM (Balke et al., 1999) and the RAX tests (Townsend et al., 1974). The RAX tests used similar tank-cars as proposed for this test series. The RAX tests showed clear evidence of fire variability from one end of the tank to the other. This was due to wind effects.

The RAX fire pan dimensions were 24.3 m long by 9.1 m wide. For the present tests a pan 24 m long by 9 m wide is proposed. This allows for 3 m of fire pan around every side of the tank-car.

The following sections include details about the fire system. It is not possible, at this time, to define certain details because of uncertainties in the fire behaviour. Several pre-test pool fire burns are planned to establish the fire behaviour before the tank is included.

4.1. Pre-Test Pool Fire Burns

A number of tests are planned to study the behaviour of the fire before a tank is put in place. These tests will be used to help define the following:

i) fuel burn rate
ii) water boil off rate
iii) instrument well temperatures
iv) fire calorimeter performance
v) fire temperatures
vi) fuel level instruments
vii) fire characteristics and geometry
viii) wind effects

The pre-test burns will probably last up to 20 minutes.

It is understood that the fire behaviour will change when the tank is in position. It is expected that the fire burning rate and temperatures will be reduced when the tank is in place.

One of the later pre-test burns will include a, 1900 or 3800 L (500 or 1000 gallons) propane tank filled with water. This tank will include lading, wall and jacket thermocouples, and pressure sensors. It will also be connected to the vapour vent and liquid drain lines. The vapour vent system will be used to maintain the tank pressure below 70 kPaG (10 PSIG). The purpose of this test is to fully check the data acquisition and control system under fire conditions.

4.2. Wind Effects

Even a light breeze, below 3 m/s (11 km/h) will have a strong effect on the fire conditions, especially if the direction is not constant. This was observed by Keltner and

Bainbridge when dealing with large pool fires 9.1 m wide by 18.3 m long (1988). The wind produces a tilt in the flame as well as altering the mixing and combustion in the fire. The fire tilt can cause objects within the fire pit to be alternately engulfed and not. Using the technique of Welker and Sliepevich (1966) the angle of tilt was correlated to wind speed in Figure 11. At 3 m/s (11 km/h) the flame tilt is 20°.

Wind also moves the base of liquid fuel pool fires, causing flame trailing. The vaporized fuel has a higher density than air, so it does not rise until it is heated by the combustion process. This results in the flame spreading over the ground downwind, beyond the fire pan, and causes the fire to remain low on the upwind side of the fire pan. This can cause incomplete engulfment of the tank-car on the upwind end, even when flame tilt alone would indicate that the tank-car will remain fully engulfed.

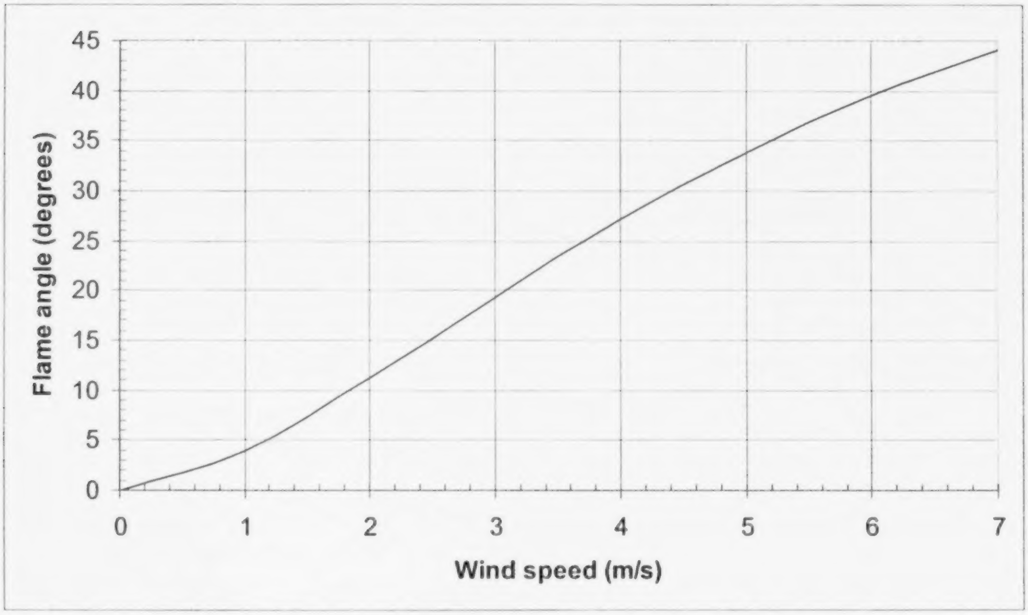


Figure 11: Bending of flame from vertical with wind blowing along long axis of 24 m by 9 m kerosene pool fire using technique of Welker and Sliepevich (1966)

Past full-scale tests have attempted to control wind by building large berms around the test site. These berms were also intended capture projectiles and absorb the blast in case of a tank-car failure (Townsend et al., 1974), (Balke et al., 1999). The berms imposed artificial wind conditions and blocked the flow of combustion air into the fire. It was observed that the fire was hotter near the opening in the berm. The berms also alter the blast and projectile pattern. This is an undesirable effect in this test series. If a tank-car does fail the resulting damage data (blast, projectile and thermal radiation) is valuable information. Since very few tests of this scale are performed, the opportunity to observe the effects of failure should not be ignored.

To reduce the wind effect on the tests they will be performed under low wind conditions. Typically this will occur early in the morning or later in the evening. A PC based weather station recording local barometric pressure, temperature, humidity, wind speed and direction should be installed as early in the test set-up as possible to determine the wind patterns over a typical day. The patterns can then be used to determine the best time to perform the test.

Wind direction is also an important factor. The prevailing wind should blow down the long axis of the tank-car to reduce the fraction of the tank-car affected by flame trailing and tilt. Figure 12 shows a possible engulfment of the tank-car with the wind blowing from the end. This results in about 8% of the tank-car not being engulfed. In contrast, Figure 13 shows a possible engulfment with a wind blowing across the tank-car, which results in 25% of the tank-car not engulfed.

The tank-car will be installed with the prevailing wind blowing along the axis of the tank-car. The test will be performed when the wind is blowing along the axis and at a time of day when it is not expected to change direction. The wind will be limited to 11 km/h (3 m/s). This value will be reassessed once the initial pre-test burns have been performed, and the effect of the wind on the particular set-up and geography can be observed. Additional pre-test burns should be performed if any doubt remains about the effect of the achievable wind conditions on the fire.

4.3. Pool Fire

The design of the pool fire system is a critical component of these tests. The response of the tank is driven by the fire. The objective is to simulate a worst case engulfing fire scenario, which means the following:

i) 100% engulfing
ii) luminous (primarily radiative)
iii) steady (constant size, shape, average temperature, etc)

When the RAX tests were conducted, the pool fire provided a heating environment equivalent to a 100% engulfing fire with a black body radiating temperature of 871°C plus or minus 56°C (1600°F plus or minus 100°F). It is known that the RAX tests were not 100% engulfing due to wind effects. This means the actual fire temperatures where the tank was engulfed were higher than reported above.

There will be no control over the fire temperature during the tests. However, the fire temperature occurring will be measured.

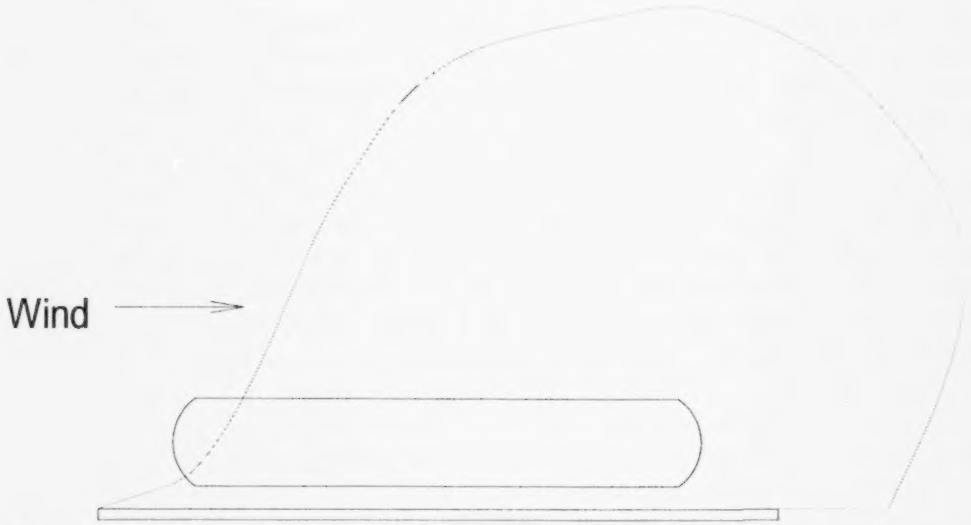


Figure 12: Wind blowing from end of tank-car showing possible flame boundary

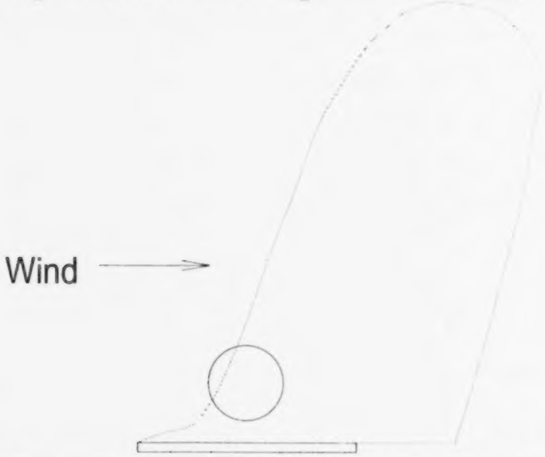


Figure 13: Wind blowing from side of tank-car showing possible flame boundary

4.3.1. Pool Fire Fuel Demand

The fire pan will contain a pool of JP-4 floating on top of water. The water ensures a level surface, even distribution of the fuel, and keeps the fire pan cool. The evaporation of the fuel is driven by radiative heating from the fire. The evaporation rate is dependent on pool size, until the pool is large enough that the surface sees only flame and none of the surroundings. The pool fire in this test exceeds that limiting size.

The evaporation rate is the same as the burn-off rate, and is important to ensure that adequate fuel is available to complete the test. Table 10 gives results from several authors for the fuel consumption rates in large pool fires. The RAX tests, which are nearly identical to this work, have a significantly higher rate than the others. Pritchard and Binding (1992) report a fuel regression rate of 7.4 mm/min for kerosene (JP-4 is a particular specification of kerosene with lighter hydrocarbons added), which is closer to the RAX results than the others. In the RAX tests the containment of the pool fire in a pit may have affected the evaporation rate of the fuel, and the presence of the tank-car also had an effect. We have designed this test based on the RAX tests fuel consumption rate, since it is the closest to this set up, and the worst case.

We expect to use a liquid fuel depth of between 25 and 100 mm. This means when the fuel pumps are turned off it will take between 5 and 20 minutes for the fire to burn out. We want to use as thin a fuel layer as possible to have good control over the fire. The actual level will be established during pre-test burns.

Table 10: Fuel consumption rates and volume required for 100 minute test for JP-4 pool fires

Regression Rate (mm/min)	Required Volume (kL)	Required Volume (US Gal)	Source	Notes
8.3	178	47,000	RAX 1 (Manda, 1975)	Identical pool fire to these tests, but enclosed in a pit 46 m x 30 m x 8 m deep
8.4	182	48,000	RAX 2 (Manda, 1975)	
4.4	94	25,000	(Rew et al., 1997)	Validated with others experimental. work
5.5	120	32,000	(Raj, 1981)	Circular 15.24 m diameter pool

4.3.2. Pool Fire Water Demand

It is important that the pan does not overflow, that we do not run out of fuel prematurely, and to keep the overall liquid level nearly constant in the pan to maintain steady fire conditions. To achieve this, without increasing the depth of the fuel, both the fuel and water levels must be managed.

Energy transferred to the pool that is not used to evaporate the fuel will heat the water below, eventually causing it to boil. This phenomenon, known as boil over, can increase fuel burn-off rate, but Chatris et al. (Chatris et al., 2001) found that this depended on the ratio of fuel depth to pool area. For diesel fuel they found no increase in burn-off for a ratio of less than 1.5 mm/m^2. If the fuel layer in this test is limited to a maximum of 100 mm the ratio becomes 0.5, significantly less than 1.5. Diesel and JP-4 have similar density, boiling points and fuel consumption rates, so it is unlikely that boil over will have a significant effect on burn-off in this test series.

Heat from the fire will reduce the water level in the pool. Based on initial fuel and water temperatures of 25°C, a blackbody fire temperature of 927°C and a fuel evaporation rate of 5 mm/min, we estimate 150 mm of water will evaporate during the 100 minute test, based on an energy balance. However, with an 8 mm/min regression rate and fire temperature of 815°C, no water will evaporate.

A layer of water 600 mm deep will ensure an adequate water depth at all times. The heating of the water will raise the water level around 25 mm, compensating for some evaporation. Pre-test burns will be conducted to determine if water should be added during a 100 minute burn.

4.3.3. Fuel and Water Level in Pan

It is important that the pan does not overflow and that we do not run out of fuel prematurely. The total liquid level will be continuously monitored in a remote sump, and the upper and lower limits verified by thermocouples in the fire pan. The levels in the fire pan are shown in Figure 14 with fuel and water at the initial conditions. It also provides the extreme boundaries of the water level due to heating and evaporation, without water makeup. A 50 mm dead zone is provided between the thermocouples. This corresponds to 6 to 10 minutes of burn-off before the pump has to restart.

The level float will be located in a remote sump 10 m away from the fire pan on the up wind side. The sump will connect to the fire pan by a 2.5 cm (1 inch) pipe. The sump will contain water only and the levels will, therefore, be slightly different than the levels in fire pan due to the difference in density of JP-4 and water. The difference in levels could be calculated, but the simplest solution is to measure the depth during the initial filling process. When the JP-4 reaches the lower limit the depth will be recorded and again when the upper limit is reached. The difference in temperature between the sump and fire pan will also create an error. Thermocouples will be installed in the water of the sump and fire pan to compensate for this. The compensation will be done by the DAC computer. The sump will have to be covered with 30 cm of earth and vented to atmosphere. Figure 15 shows the sump with the depth sensor.

Back up fuel control is performed by upper and lower limit thermocouples. When the lower limit thermocouple is exposed to the hot gasses over the liquid the high temperature triggers the fuel pump to start. When the upper limit thermocouple is immersed the low temperature triggers the pump to stop. Figure 14 shows the control thermocouples in the fire pan. The thermocouples will be supported by 2.5 cm (1 inch) angle welded to the bottom of the pan and terminating 5 cm below the thermocouple tip. Two of each thermocouple should be installed in case of failure. An additional thermocouple is installed in an overflow sump. The fire pan wall bordering the sump is 3 cm below the remainder. Details on the overflow sump are shown in Figure 16. If the pan is approaching overflow the sump will fill, cooling the thermocouple, and triggering a shutdown of the pump. The required thermocouples and depth gauge are summarised in Table 11.

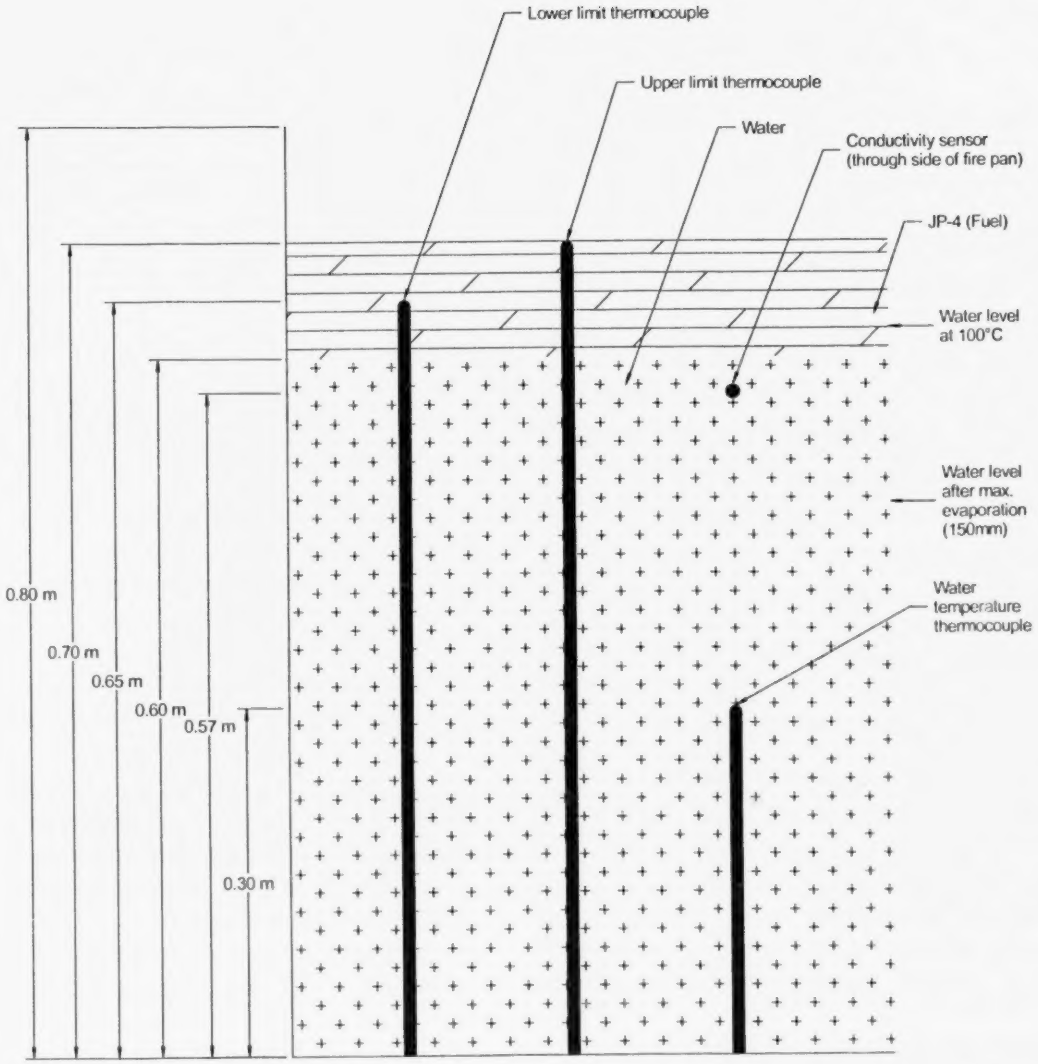

Lower limit thermocouple
Upper limit thermocouple
Water
Conductivity sensor (through side of fire pan)
JP-4 (Fuel)
Water level at 100°C
Water level after max. evaporation (150mm)
Water temperature thermocouple
0.80 m
0.70 m
0.65 m
0.60 m
0.57 m
0.30 m

Figure 14: Cross section of fire pan showing fill levels and control thermocouples

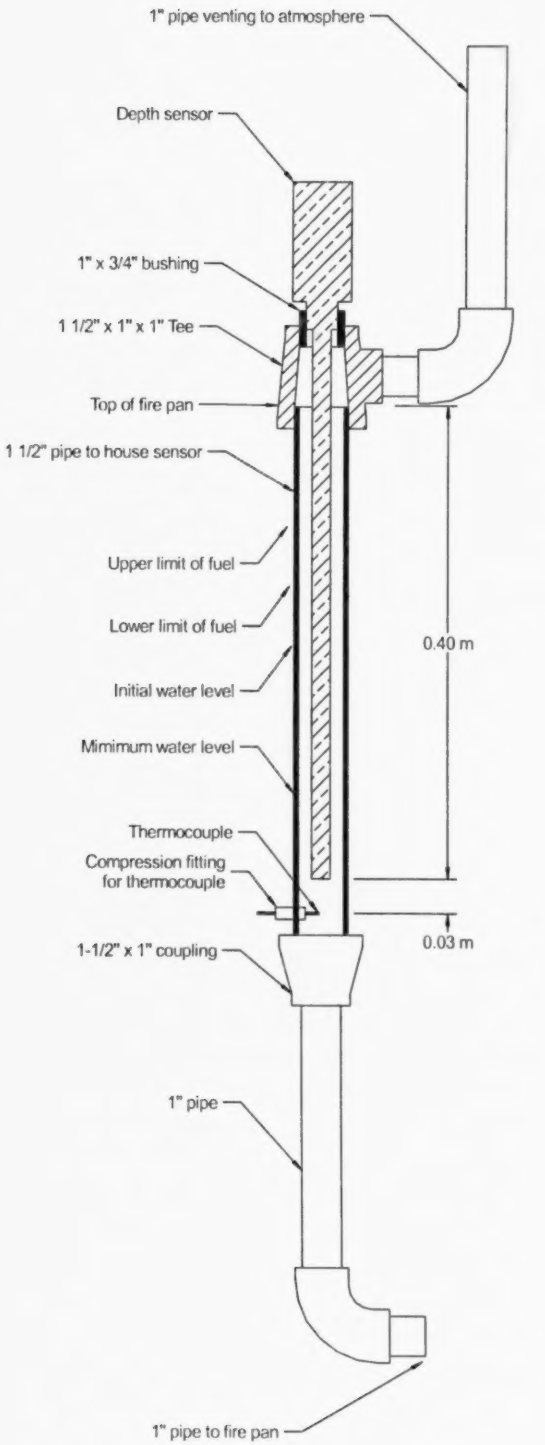

1" pipe venting to atmosphere
Depth sensor
1" x 3/4" bushing
1 1/2" x 1" x 1" Tee
Top of fire pan
1 1/2" pipe to house sensor
Upper limit of fuel
Lower limit of fuel
0.40 m
Initial water level
Mimimum water level
Thermocouple
Compression fitting for thermocouple
0.03 m
1-1/2" x 1" coupling
1" pipe
1" pipe to fire pan

Figure 15: Fire pan remote liquid level sump

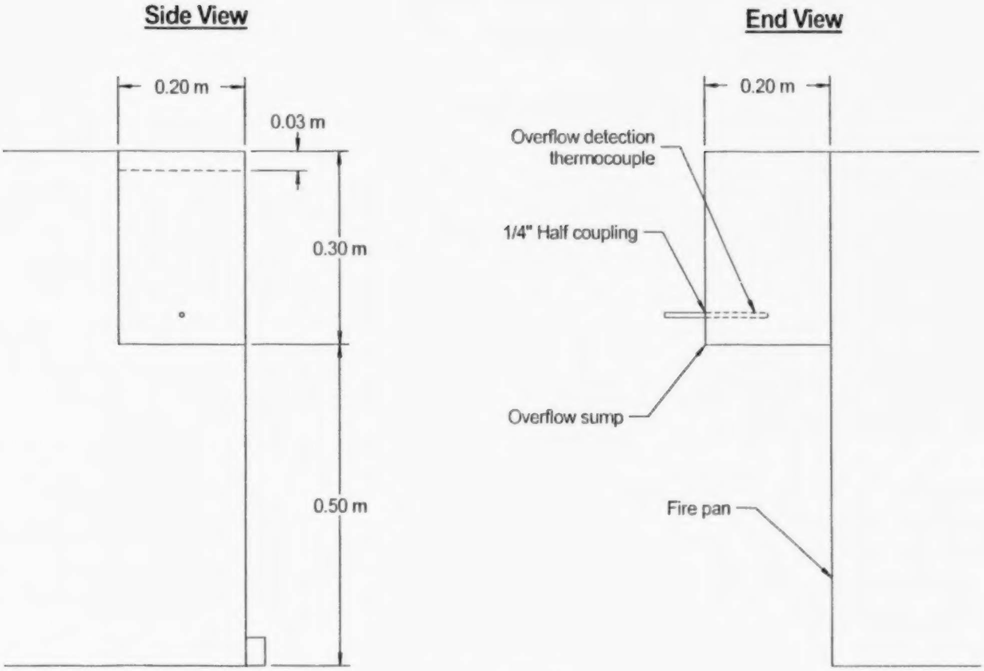


Figure 16: View of overflow sump attached to fire pan

Figure 14 also shows a conductivity sensor positioned 3 cm below the bottom of the fuel. This sensor should detect if the water at this point is replaced by JP-4, by detecting the drop in conductivity. The conductivity of fresh water is 100×10^{-6} to 300×10^{-6} S/cm, while kerosene is about 0.4×10^{-12} S/cm (JP-4 will be very similar to this). Any sensor with a range to measure the water conductivity will measure 0 for JP-4. A sensor with a 0 to 200×10^{-6} S/cm range should be used. This will read 0 for JP-4 and between 0.5 and 1 of full range for water. The required components are given in Table 11.

After the probe detects JP-4 the pump will be activated for enough time to bring the water back up to the original level. The time could be adjusted after the pre-test burns to compensate for boil off occurring, but it should always be limited to maintain the top of the water below the minimum fuel level if no boil off is occurring. By limiting the time that the pump can run if the conductivity sensor fails it will not cause all the fuel to be displaced by water, ending the test prematurely. To reactivate the water pump the sensor will be required to once again detect the presence of water followed by JP-4.

The probe is limited to 120°C which could be exceeded in the JP-4, but near the water interface it should not be too far from 100°C and the probe should only be exposed to JP-4 for a short time. A less expensive, heat tolerant, option would be a float system. The floats would have a specific gravity less than water at 100°C (SG=0.96) but greater than JP-4 at ambient ($SG_{maximum}$ =0.80). Unfortunately the recommended difference in float and liquid specific gravity is 0.3, which exceeds the difference between water and JP-4.

This means that to ensure the float will work in water under all conditions a specific gravity of 0.66 is recommended, which would likely float in JP-4.

Table 11: Fuel and water control sensor specifications

Purpose	P/N (Omega)	Quantity
Level transmitter	LVCN-82-18	1
Sump T/C	K-type Omega Clad 1/8 inch diam.	1
Fire pan water T/C	K-type Omega Clad 1/8 inch diam.	1
Upper limit T/C	K-type Omega Clad 1/8 inch diam.	2
Lower limit T/C	K-type Omega Clad 1/8 inch diam.	2
Overflow detection T/C	K-type Omega Clad 1/8 inch diam.	1
Conductivity transmitter	CDTX-1204 (0.0-199.9μS/cm)	1
Submersible conductivity probe	CDE-1202	1

To ensure the fire pan never flows into the instrument well the wall around it is 5 cm higher than the wall around the exterior of the pan. Figure 17 is a drawing of the fire pan, showing the plan and side views. The pan will be constructed of 10 gauge steel, with an average thickness of 3.4 mm (0.1345 inches). Concrete blocks will be placed against the outside of the pan for support.

4.4. Ignition

The pool fire will be ignited by two utility burners, supplied by a single 20lb propane cylinder. The cylinder will be located near the calorimeter water tanks and protected from the pool fire. The propane flow will be controlled with a pressure regulator and solenoid valve, and the propane ignited with a spark plug connected to an industrial spark generator. A manual shut off valve will also be installed at the burner. After the pool fire has been ignited the burners will be left on to allow the cylinders to empty.

The burners will be positioned at the corners of the fire pan at the upwind end. Figure 18 shows the burner connected to the propane source. Prior to adding fuel to the fire pan, the burners will be positioned and the fuel pressure adjusted to ensure the flame makes good contact with the pool surface. Once the pool has ignited it will rapidly spread over the entire surface. A single burner would be adequate for ignition, but a second is included for backup. Table 12 gives the required components for the ignition system. The system should survive from test to test, but some copper tubing may need replacing.

Table 12: Pool fire ignition system components

Part	Quantity
Propane Utility Burner	2
Ignition coil	2
Solenoid valve, 1/8 inch, Viton seal, 300 PSIG, 120V	1
Regulator	1
20lb Propane cylinder	1
Copper tube and fittings	1

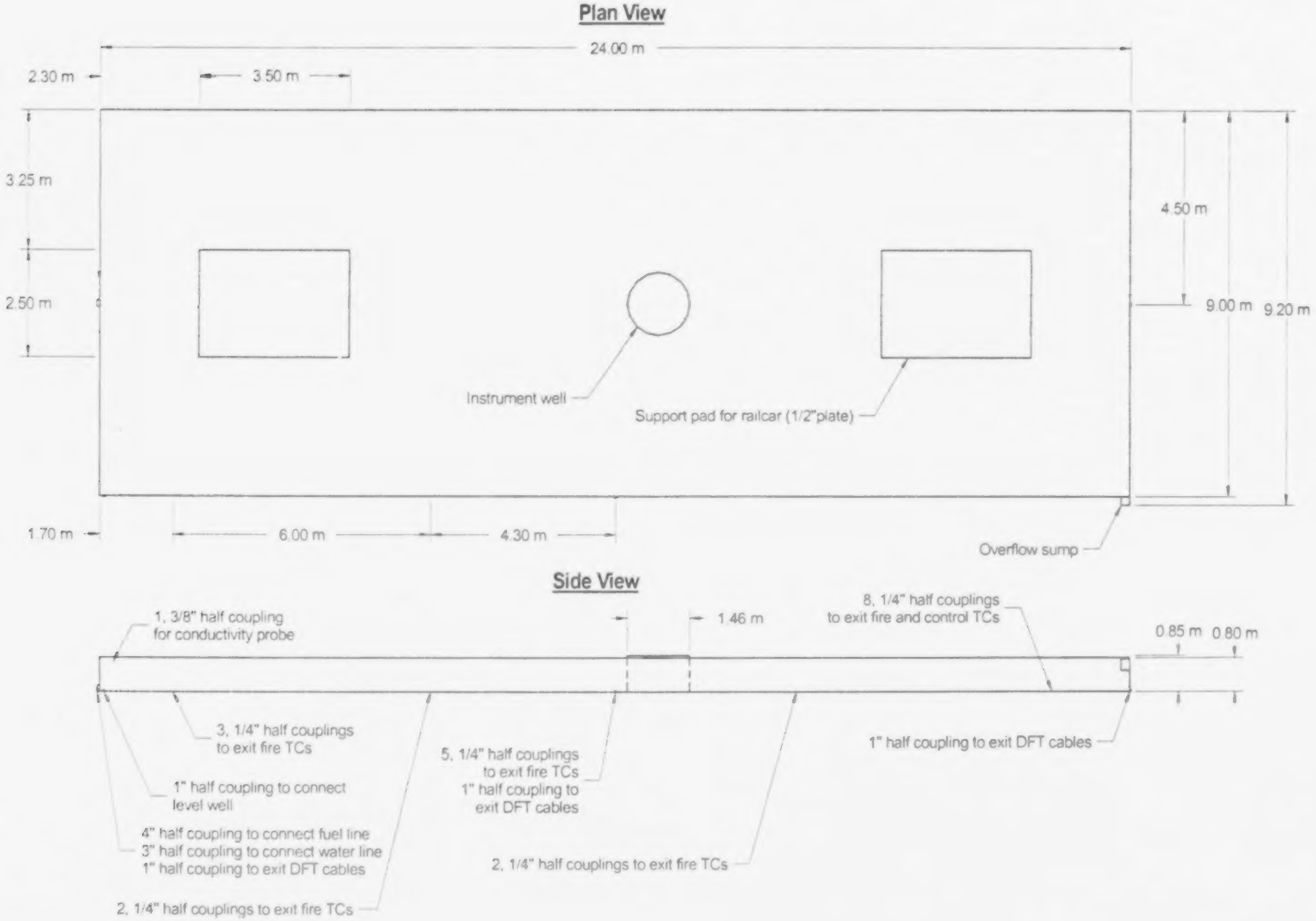
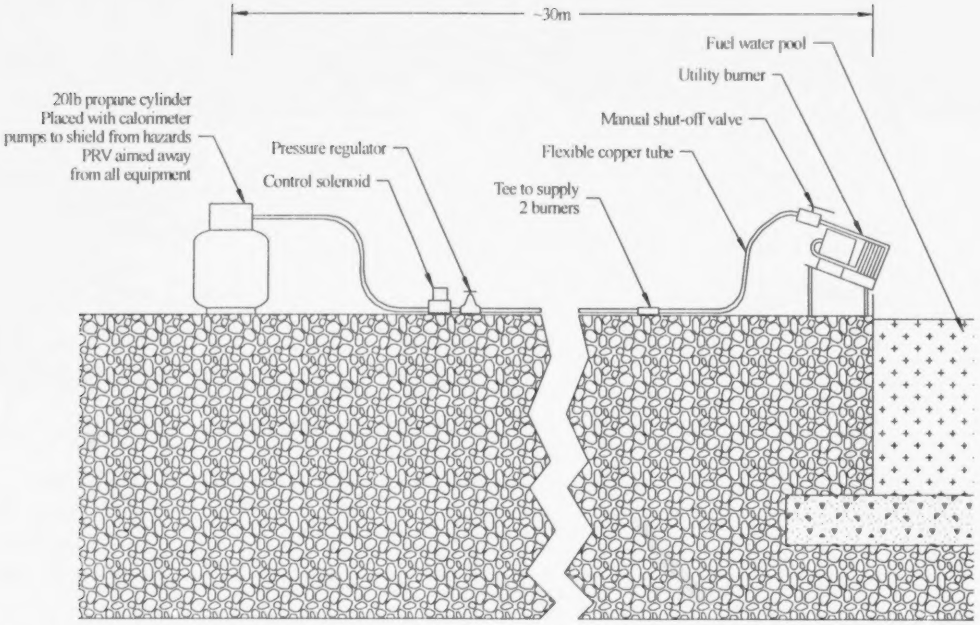

Plan View
24.00 m
2.30 m
3.50 m
3.25 m
2.50 m
4.50 m
9.00 m
9.20 m
Instrument well
Support pad for railcar (1/2"plate)
1.70 m
6.00 m
4.30 m
Overflow sump
Side View
1, 3/8" half coupling
for conductivity probe
1.46 m
8, 1/4" half couplings
to exit fire and control TCs
0.85 m
0.80 m
3, 1/4" half couplings
to exit fire TCs
1" half coupling to connect
level well
4" half coupling to connect fuel line
3" half coupling to connect water line
1" half coupling to exit DFT cables
2, 1/4" half couplings to exit fire TCs
5, 1/4" half couplings
to exit fire TCs
1" half coupling to
exit DFT cables
2, 1/4" half couplings to exit fire TCs
1" half coupling to exit DFT cables

Figure 17: Plan and side view of fire pan


~30m
Fuel water pool
Utility burner
Manual shut-off valve
Flexible copper tube
Tee to supply 2 burners
20lb propane cylinder Placed with calorimeter pumps to shield from hazards PRV aimed away from all equipment
Pressure regulator
Control solenoid

Note: 2 burners to be installed at upwind end of fire pan approximately 4.5m apart - 2.25m from sides

Figure 18: Fire pan ignition system

4.5. Fuel and Water Delivery

A 100 minute test could require as much as 182 m^3 (48,000 gallons) of JP-4. The pre-test burns may allow a more accurate estimate of the fuel required, but it is preferable to have excess fuel, rather than insufficient to complete the test.

The fuel will be stored in two 114 m^3 (30,000 gallon) tanks, 200 m away and upwind from the test site. A third tank will be used for water storage. An earth berm or concrete block wall will be constructed around the front and the sides of the tanks, as shown in Figure 19. The berm is positioned to minimize obstructing the view from the control bunker and camera locations.

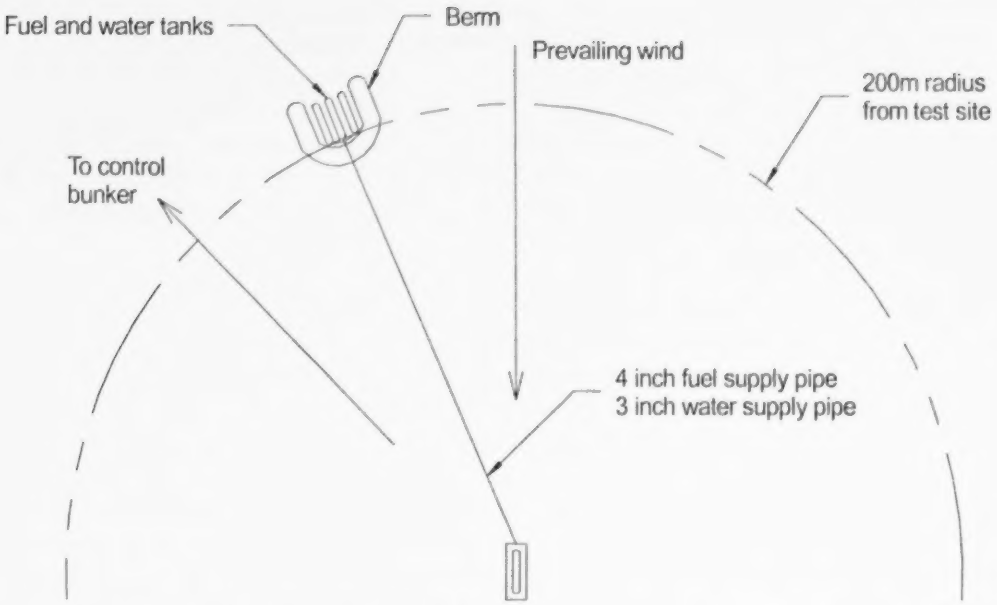


Figure 19: Layout of fuel and water tanks

The fuel pump will have to meet the following specifications:

- Minimum 35 L/s (560 US gal./min)
- Discharge pressure 280kPa (41 PSI) at 35 L/s
- Handle kerosene (JP-4)

This is the equivalent of a 10 mm/min burn-off rate if the pump operates continuously. The discharge pressure allows for a 10.2 cm (4 inch) diameter pipe from the fuel tank to the fire pan. If the pump can handle water in addition too JP-4, it will be able to return the water from the fire pan to a 114 m^3 (30,000 gallon) water storage tank, at the conclusion of the test.

A smaller pump would be required to deliver makeup water to the pan. The minimum flow rate for this pump should be 15 L/s (240 US gal./min). The maximum average expected boil of rate is estimated at 5.5 L/s, but the evaporation could be concentrated in the later half of the test after an initial period of heating. This could result in a maximum local evaporation rate approaching 9 L/s. However, the addition of fuel and water during the test will require continuous heating preventing the estimated maximum from being reached. The water could be pumped through a 7.6 cm (3 inch) pipe. This would require the following pump specifications:

- Minimum 15 L/s (240 US gal./min)
- Discharge pressure 280kPa (41 PSI) at 15 L/s
- Handle water

To maintain prime the pumps will be located below both the fuel tanks and the fire pan. A set of valves will be required to direct the water pump inlet and outlet to the correct location so it can either drain or supply the fire pan. These valves will be manually operated, as this will be done once the test site has cooled down. The system presented here assumes that a supply system is dedicated to both fuel and water supply. Appendix G gives a setup to allow one pump to supply either fuel or water. This could be used if no water makeup system was installed or for the water pump to act as a backup fuel pump.

A valve system will be required to allow the pumping of fuel or water, to and from, the fire pan. A schematic of the system is given in Figure 20. The valve settings to perform the various pumping functions are given in Table 13. The settings to allow fuel to flow during the test are highlighted. In addition to removing water after the test, this system can remove rain water that has collected in the fire pan.

During the test the manual valves will be set to the "Operate Test" function, and the automated valves opened and closed as required. The automated valve has to open prior to starting the pump and close after the pump has stopped. This will require two digital outputs from the DAC board. The components for the fuel and water delivery system are given in Table 14.

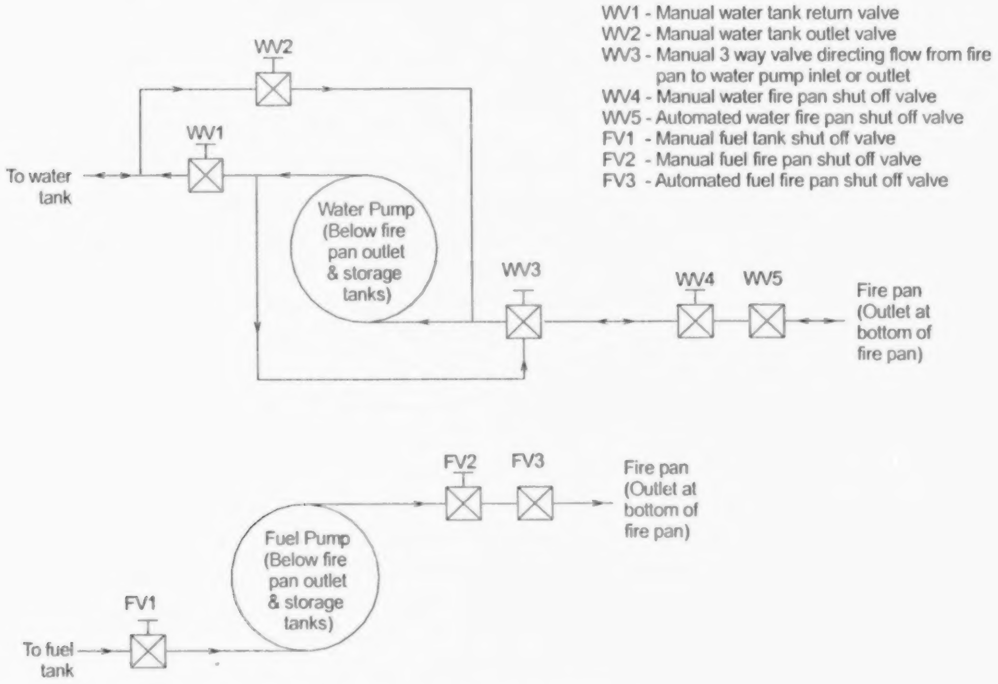

WV1 - Manual water tank return valve
WV2 - Manual water tank outlet valve
WV3 - Manual 3 way valve directing flow from fire pan to water pump inlet or outlet
WV4 - Manual water fire pan shut off valve
WV5 - Automated water fire pan shut off valve
FV1 - Manual fuel tank shut off valve
FV2 - Manual fuel fire pan shut off valve
FV3 - Automated fuel fire pan shut off valve
WV2
WV1
To water tank
Water Pump (Below fire pan outlet & storage tanks)
WV3
WV4
WV5
Fire pan (Outlet at bottom of fire pan)
FV2
FV3
Fire pan (Outlet at bottom of fire pan)
Fuel Pump (Below fire pan outlet & storage tanks)
FV1
To fuel tank

Figure 20: Schematic of pumping and valve system

Table 13: Valve positions to perform required pumping functions

Valve	Operate Test	Water to Fire Pan	Fuel to Fire Pan	Drain Fire Pan of Water	Notes
WV1	Closed	Closed	N/A	Open	Manual valve
WV2	Open	Open	N/A	Closed	Manual valve
WV3	Outlet	Outlet	N/A	Inlet	3-way valve connects fire pan to either pump inlet or outlet
WV4	Open	Open	N/A	Open	Manual valve
WV5	Open/Close as required	Open	N/A	Open	Automated valve for control during test
FV1	Open	N/A	Open	Closed	Manual valve
FV2	Open	N/A	Open	Closed	Manual valve
FV3	Open/Close as required	N/A	Open	Closed	Automated valve for control during test

Table 14: Fuel delivery system components

Component	Quantity
4" Piping	1
Pump 560 USGPM@92 ft. water head	1
25HP motor	1
4" Brass ball valves	2
4" 3-way valve	1
4" Actuated valve	1
3" Piping	1
Pump 240 USGPM@92 ft. water head	1
10HP motor	1
3" Brass ball valves	3
3" 3-way valve	1
3" Actuated valve	1

4.6. Ground Preparation

The ground under the fire pan will have to support the weight of the pan, water, fuel and tank-car. In addition, it will contain any fuel that may spill from the fire pan during a test. This is achieved by spreading a base layer of gravel, laying down an oil resistant membrane and a top layer of gravel. Under the fire pan a layer of concrete slabs will provide a solid base for the pan and tank-car.

Figure 21 shows a cross section of the required ground support. The depths represent the minimum required to pass the instrumentation cables under the fire pan. The membrane will extend 3 m beyond the fire pan and slope upwards so that the edge is at ground level. The membrane will also have to be installed at an angle towards a drain point to remove rain water by a small pump. The design will be reviewed by qualified civil engineers for drainage and support.

This system will catch any overflowing fuel, but it may not provide containment if the tank-car fails. The range of fuel dispersal in that case could be large, but it is expected that the ensuing fireball will burn-off most of the dispersed fuel. The chances of this are improved due to the ground heating from the pool fire which will help evaporate the JP-4 when it contacts the surface.

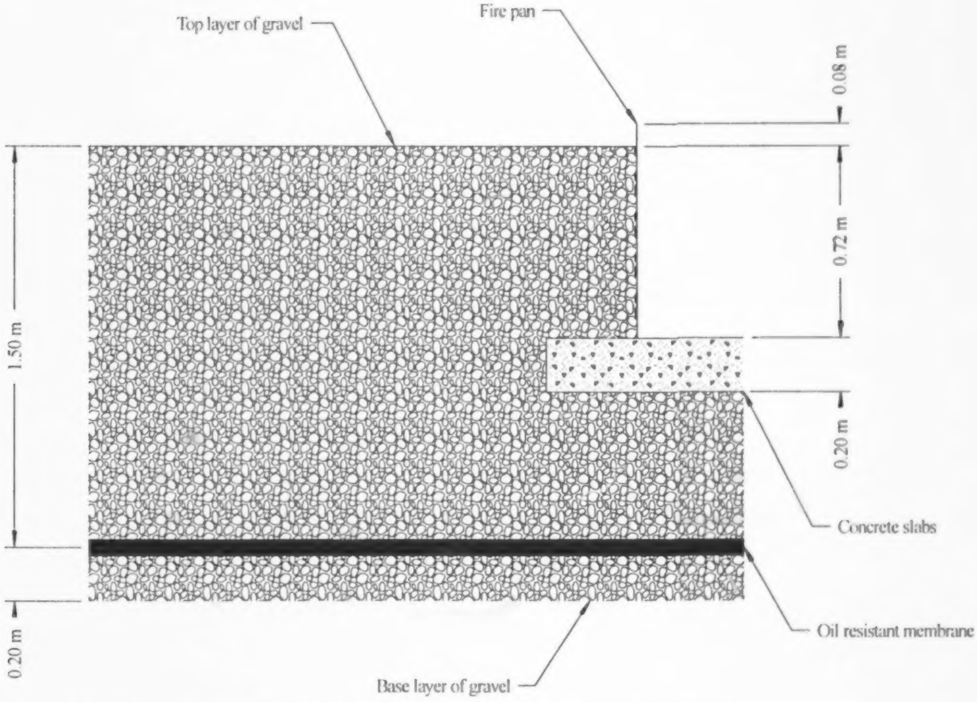


Figure 21: Cross section of required ground support for fire pan

4.7. Cable Protection

Since the tank-car is in an engulfing pool fire all the cables from instrumentation in the tank-car must be protected as they pass through the fire. A pool fire of this size significantly heats the surroundings and the cables must also be protected once they have left the fire pan. A failure of the tank-car will create a large fireball, and it would be advantageous to protect the cables from this source of heat, since it would reduce the time and cost of recovery.

4.7.1. Instrument Well

The instrument well provides protection from the fire for the cables that exit from the bottom of the tank-car, to below the fire pan. The only source of cooling for this well is the tank-car surface, which is cooled by the liquid propane on the inside. The surface of the tank-car inside the well will be stripped of insulation to allow the attachment of feed throughs and for cooling of the well. If the tank-car surface is un-insulated in the well the modeled well air temperature reached 310°C. The outer tank-car wall temperature in the well was not significant in either case, 68°C for the un-insulated case and 65°C for the insulated case. The well is fully insulated, so that the tank wall in the well is effectively thermally protected. Details of the well heat transfer analysis can be found in Appendix H.

A cross-section of the instrument well is shown in Figure 22. Thermocouple connections and transducers will be below the fire and under the fire pan, in the connection well, with a thick layer of insulation protecting them from the upper well. This will protect them from overheating and shield the cables in case the tank-car fails. The vapour vent and liquid drain lines will be schedule 80 in the well to help withstand the high temperatures.

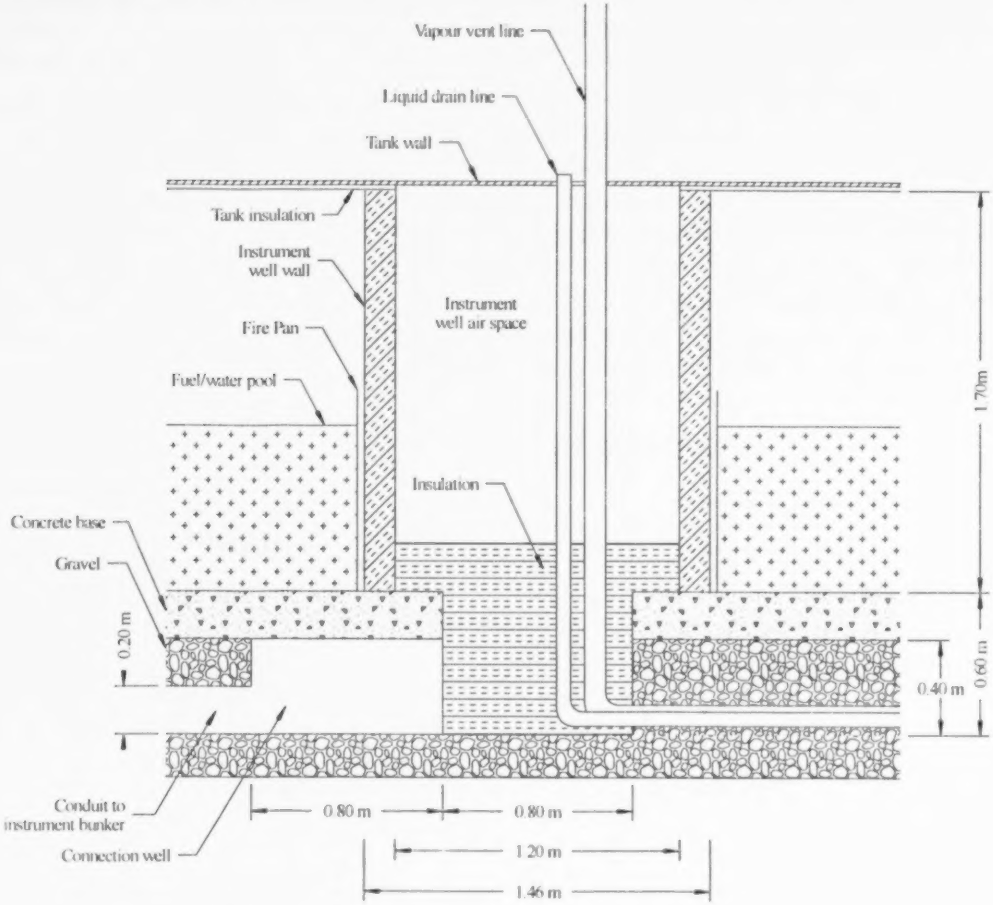

Vapour vent line
Liquid drain line
Tank wall
Tank insulation
Instrument well wall
Fire Pan
Fuel/water pool
Instrument well air space
Insulation
Concrete base
Gravel
0.20 m
1.70m
0.60 m
0.40 m
Conduit to instrument bunker
Connection well
0.80 m
0.80 m
1.20 m
1.46 m

Figure 22: Cross section of instrument well

4.7.2. Buried Cables

Beyond the fire pan the cables will be exposed to thermal radiation from the large pool fire and, if the tank-car fails, engulfed in a fireball for up to 20 seconds. The easiest way to shield from this is by burying the cables. At a depth of 30 cm the cables will not feel any effects of the pool fire or fireball during the test. The ground temperature was modeled as shown in Appendix F. A 30 cm depth will be maintained to a 50 m radius.

From 50 too 150 m a 10 cm depth is adequate, to 400 m 2 cm, and to 600 m a covering, as shown in Figure 2.

After the cables run from the instrument well they pass through a connection and access box, shown in Figure 23. This allows access to the cables from the instrument well, and for connecting fire instrumentation cables to extension cables extending to the instrument bunker. If the extension cables in the well are damaged beyond repair during a test they could be cut in the connection and access box and new cables passed under the fire pan. This would prevent having to replace the cable back to the bunker. Once beyond the fire pan the conduit can be PVC, which is easier to work with and a significant cost saving over steel. The process could be further simplified by laying the cables in the trench and covering with a half pipe, to aid removal.

Fire instrument cables from either end of the tank-car are brought to the connection and access box through common conduits running the length of the fire pan. Fire instruments at the fire pan midline are taken directly into the box through individual conduits. The calorimeter and fire thermocouple probes can be passed through compression fittings to render them leak proof. Compression fittings would be used at the exit of the fire pan or calorimeter, and at the entry to an outlet box on the conduit. The outlet box would be used to connect the thermocouples to extension wire leading to the main connection and access box. In the case of the midline thermocouples no extra extension cable is required as they could be purchased with adequate cable attached.

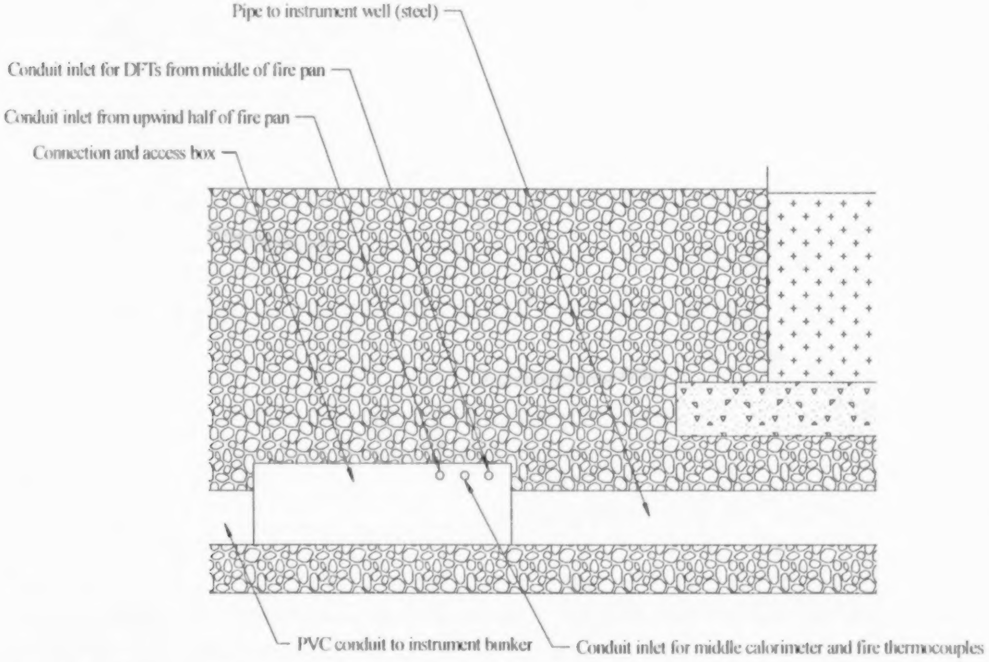

Pipe to instrument well (steel)
Conduit inlet for DFTs from middle of fire pan
Conduit inlet from upwind half of fire pan
Connection and access box
PVC conduit to instrument bunker
Conduit inlet for middle calorimeter and fire thermocouples

Figure 23: Cross section at side of pool fire showing main connection and access box

The directional fire thermometer (DFT) cables are not sheathed and can not be readily passed through a leak tight connection. Instead they pass through a pipe that rises above the fire pan liquid level. The cables can then connect to the extension cables and join the common conduit. This exit system is shown in Figure 24. The water in the piping will be hot and producing vapour. If the vapour is allowed to continue through the conduit it will cool, condense and cause liquid water to accumulate in the conduit. The piping must be vented to atmosphere and packed to prevent the vapour from entering the conduit. The DFT wires are rated to withstand the pool fire, but the riser will be buried to reduce the heating. Reduction in heating will reduce both the vapour generated and heat conducted down the pipe to the connection box, which cannot withstand high temperatures. The 20 cm of conduit prior to the connection box will be PVC so that it will melt if the conduit temperature is too high and prevent damage to cables in the connection box.

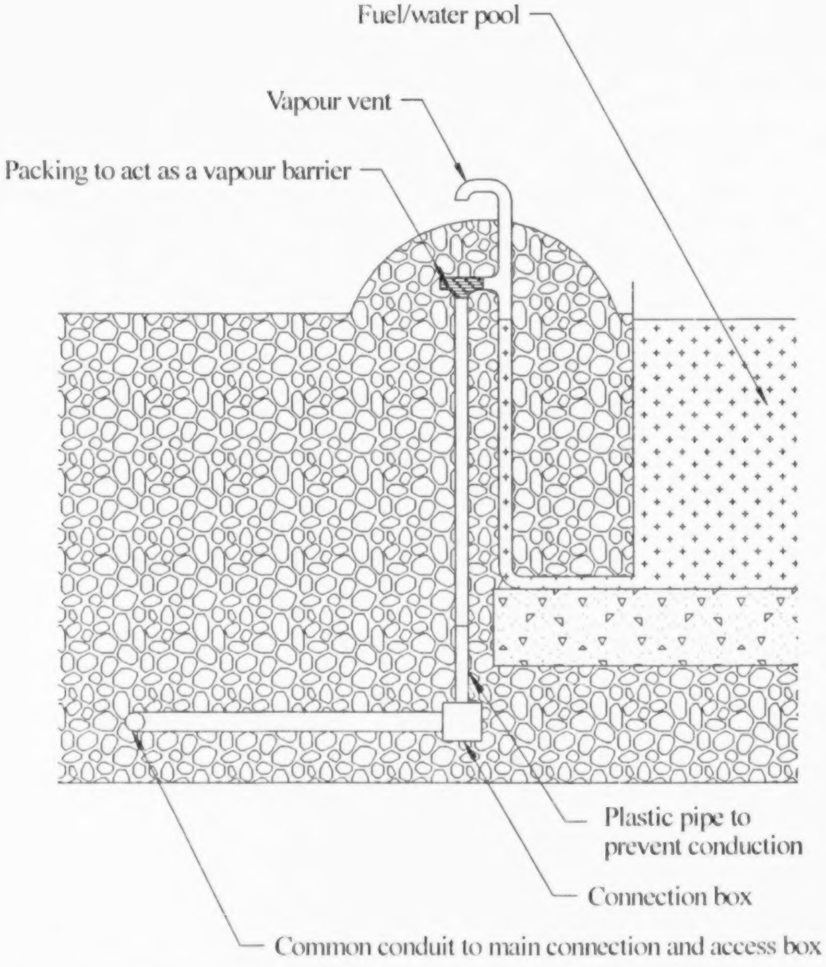

Fuel/water pool
Vapour vent
Packing to act as a vapour barrier
Plastic pipe to prevent conduction
Connection box
Common conduit to main connection and access box

Figure 24: DFT wiring exit piping from fire pan

The conduit to the instrument bunker must slope upwards, so that it passes above the maximum liquid level in fire pan, before entering the instrument bunker. Since the instrument well is below the fire pan if the pan is compromised the fuel-water mixture will flow along the pipe until it levels, which would cause the instrument bunker to fill, if the conduit does not rise above the liquid level. The elevation required to prevent the instrument bunker filling is given in Figure 25.

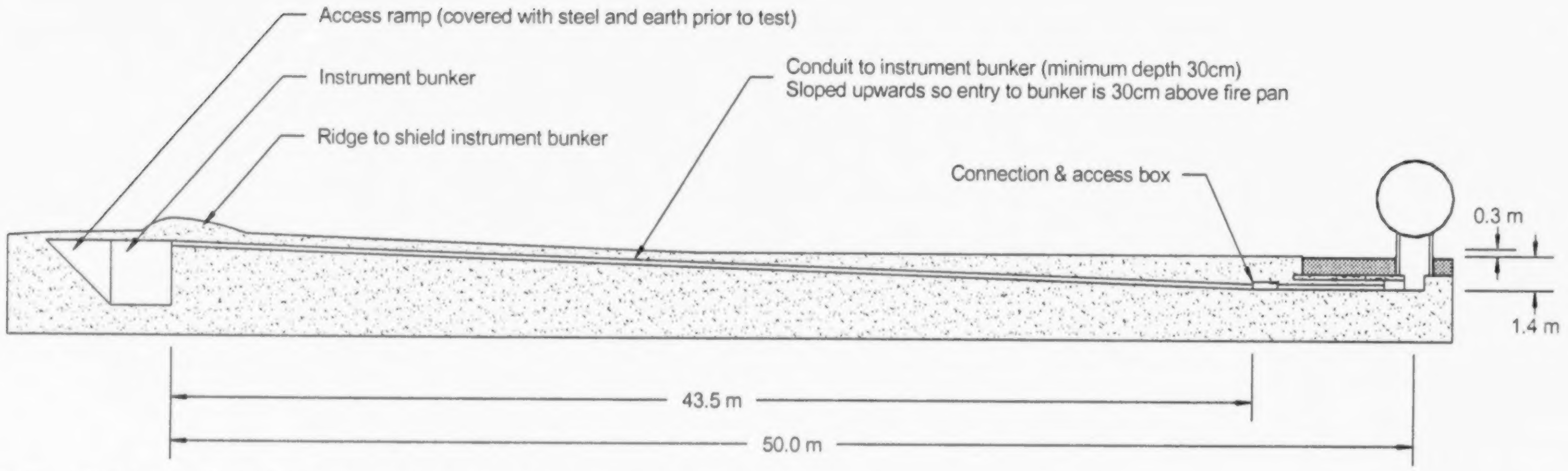

Access ramp (covered with steel and earth prior to test)
Instrument bunker
Ridge to shield instrument bunker
Conduit to instrument bunker (minimum depth 30cm)
Sloped upwards so entry to bunker is 30cm above fire pan
Connection & access box
0.3 m
1.4 m
43.5 m
50.0 m

Figure 25: Elevation view of test site along instrument bunker conduit

5. Tank-Car Instrumentation

Instruments will be added to the tank to measure the following:

- i) wall temperatures
- ii) steel jacket temperatures
- iii) liquid and vapour lading temperatures
- iv) tank pressure
- v) tank high-speed transient pressure

Tank-car instrumentation characterises the behaviour of the lading, PRV and tank-car walls. This requires sufficient thermocouples and pressure transducers to capture the desired detail. Each additional sensor adds to the test cost, but without adequate data the entire test expenditure is wasted. Given the scarcity of data on full-scale tank-cars in fires, and the interest in accurately modeling them, the opportunity should not be missed to obtain detailed data on their behaviour.

5.1. Lading, Wall and Jacket Thermocouples

The greatest number of inputs to the data acquisition system is from thermocouples measuring the temperatures on and in the tank-car. Lading thermocouples measure the temperature of the propane in both the liquid and vapour spaces. The tank-car wall thermocouples measure the temperature on the outside surface of the tank-car. Additional thermocouples are used in tests with thermal defects, to determine the temperature profile across the area with the removed insulation. Jacket thermocouples measure the temperature on the inside of the outer jacket, which covers the insulation. These help assess the fire conditions and rate of heat transfer to the tank-car. All the thermocouples are type-K, which are cost effective and can handle the high temperatures in a pool fire.

The lading thermocouples are arranged in three arrays, positioned at 25%, 50% and 75% of the inside tank-car length. At each array position, tank-car wall and jacket thermocouples are also installed. Additional wall and jacket thermocouples are positioned along the top of the tank-car. The position of each array and the wall thermocouples is shown in Figure 26. All the internal thermocouple probes and wires are routed to the bottom of the tank where they pass through the tank shell into the instrument well. From the well the wires lead to extension cables that run to the instrument bunker.

Each array consists of 76 lading thermocouple elements divided between 7 profile probes. Each probe is 0.6 cm (¼ inch) diameter and contains between 8 and 13 thermocouple elements. Figure 27 gives the details on the probe positioning. The probes are fastened to a steel frame made of 2.5 cm (1 inch) square tube, welded to the tank-car wall at the top and bottom.

The near wall profile probe is attached to spacers, tack welded to the tank-car wall, which position the probe elements 2 cm from the wall surface. The spacers conduct heat from the tank-car wall and must be positioned midway between the thermocouple elements, to minimise conduction error. Zed shaped spacers, formed from sheet metal, will also help reduce conduction. Profile probes will significantly improve the ease of installation, versus individual thermocouple probes with a similar cost.

The lading and wall thermocouple elements are aligned with the following tank-car fill levels: 0, 10, 20, 30, 40, 50, 60, 70, 80, 85, 90, 95, 99, and 100%. In addition, the profile probes intersect the top of the tank-car at the 100, 99 and 95% fill levels. The jacket temperatures are not required to be as detailed and are placed at the top, bottom, 90, 50, and 10% fill levels, resulting in 26 tank-car wall and 8 jacket thermocouples per array.

Four thermocouples are also welded on and around the PRV to obtain the outside temperature the valve is exposed to.

The centre array of thermocouples inside will provide an indication of the internal vapour temperature near the PRV. The centre array will have to be moved slightly away from the instrument well to avoid interfering with the PRV and the other piping and valves required for loading the tank-car.

All of the thermocouples external to the tank-car are produced from high temperature thermocouple wire. Type K, 20 gauge thermocouple wire, with silfa silica insulation was chosen. It is rated to 1040°C and has good abrasion resistance, reducing the possibility of problems during installation and transport.

The ends of the wire are welded to form a thermocouple element and then welded directly to the tank wall in the location of interest. As the element becomes part of the tank-car wall it obtains an excellent reading of the surface temperature. Conduction error is low because the thermocouple wire is routed under the insulation, in the same environment as the wall being measured. The wire takes the most direct route back to the instrument well. The jacket thermocouples run between the insulation and the jacket. This again reduces conduction error by placing the wire in a similar environment to what it is measuring. The wires will be exposed to higher temperatures than those under the insulation, but the maximum specification on the fire temperature is 927°C, which is below the rating of the wire, and the wires are only required to survive one test.

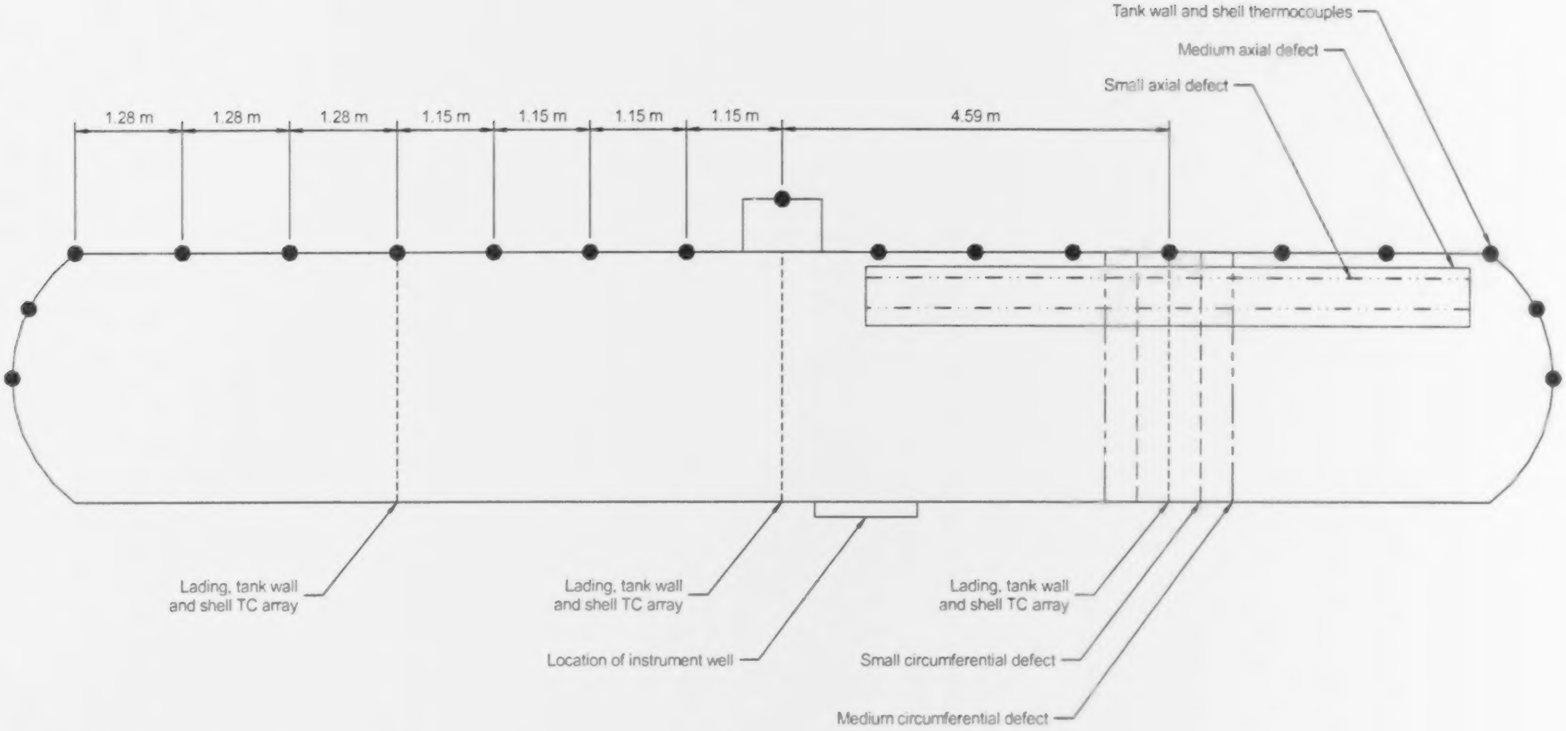
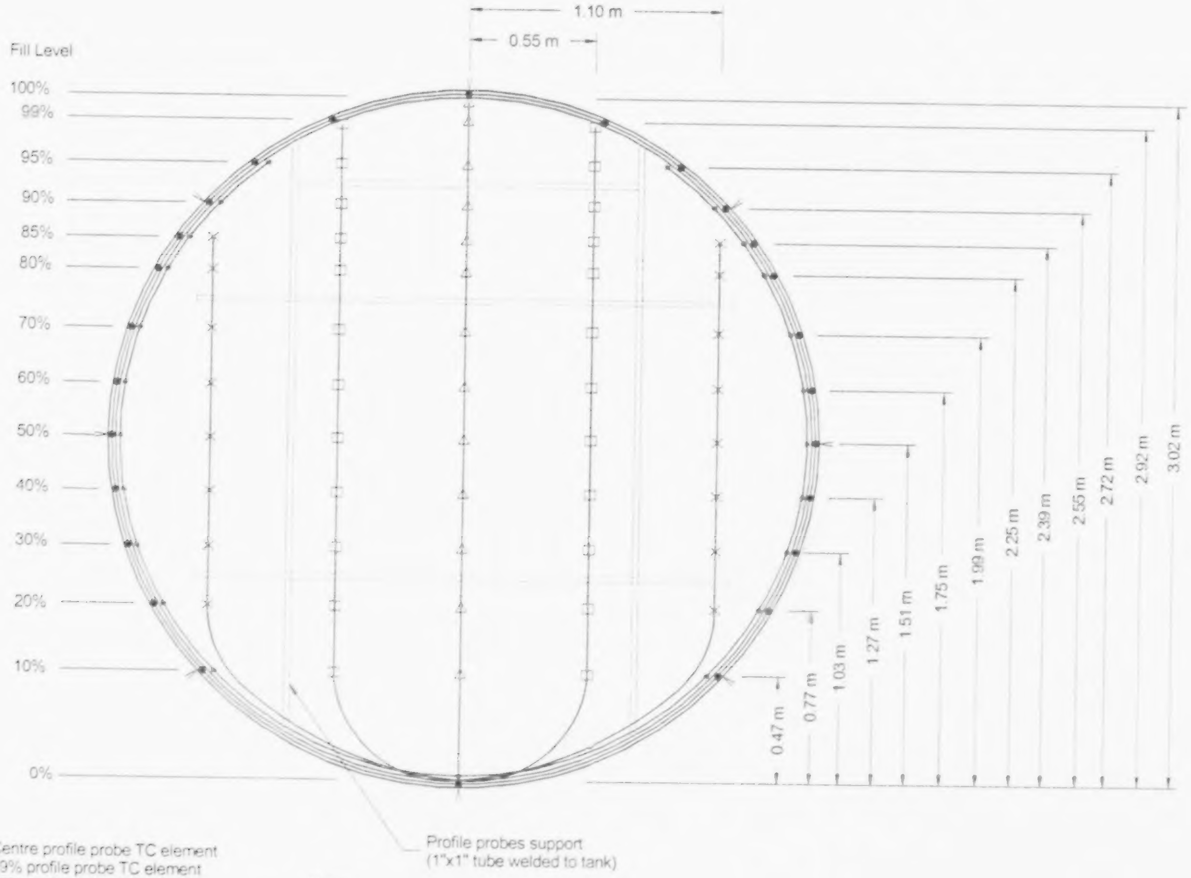

Tank wall and shell thermocouples
Medium axial defect
Small axial defect
1.28 m
1.28 m
1.28 m
1.15 m
1.15 m
1.15 m
1.15 m
4.59 m
Lading, tank wall and shell TC array
Lading, tank wall and shell TC array
Lading, tank wall and shell TC array
Location of instrument well
Small circumferential defect
Medium circumferential defect

Figure 26: Side view of tank-car showing thermocouple and insulation defect locations


1.10 m
0.55 m
Fill Level
100%
99%
95%
90%
85%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.47 m
0.77 m
1.03 m
1.27 m
1.51 m
1.75 m
1.99 m
2.25 m
2.39 m
2.55 m
2.72 m
2.92 m
3.02 m
Profile probes support
(1"x1" tube welded to tank)

△ Centre profile probe TC element
□ 99% profile probe TC element
× 95% profile probe TC element
• Near wall profile probe TC element
● Tank wall TC (welded to outside of tank)
⋎ Shell TC (welded to inside of shell)

Note:
Profile probes are attached to supports with rigid metal clamps for 1/4" tube
Top TC elements on centre and 99% profile probes are in the near wall position
Near wall profile probes are fastened to spacers welded to the tank wall

Figure 27: Thermocouple array showing lading, tank-car wall and shell thermocouples

5.1.1. Insulation Defects

Defects in the thermal protection system require extra thermocouples, beyond those given above for the baseline test. Thermocouple layouts for the following defects were examined:

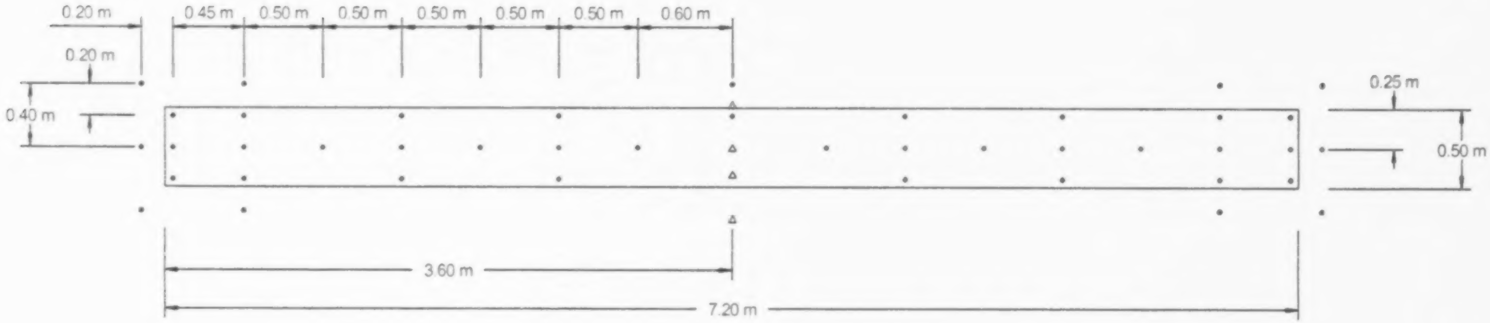
- small axial defect
- small circumferential defect
- medium axial defect
- medium circumferential defect

Each defect area has the insulation removed from under the steel jacket, but the steel jacket is left intact and separated from the tank wall by an air gap. Tank-car failure is driven by the weakening of the steel, due to heating. Therefore, it is important to determine the temperature across the defect, and in particular the maximum temperature achieved in the defect region. Cooling of the defect region occurs by conduction through the tank wall to the insulated walls, and by convection and radiation to the tank lading. In the liquid wetted region the convective heat transfer is very high and the wall will have a temperature near that of the liquid. In the vapour space the total convective and radiative cooling of the wall is much less effective, and high wall temperatures are possible. The maximum temperature is, therefore, most likely to occur along the midline of the defect in the vapour region.

Based on this reasoning, the defect thermocouples are concentrated along the midline, with others stretching to the sides and under the insulation to provide the temperature distribution in and around the defect. The proposed thermocouple layout for the small axial defect is given in Figure 28, medium axial in Figure 29, small circumferential in Figure 30 and medium circumferential in Figure 31. The axial defects are centred vertically on the 90% fill level. The thermocouple positions in the circumferential defects correspond to the heights of the wall thermocouples in the array. Each of the defects is centred on the downwind thermocouple array, which reduces the number of extra thermocouples required. The proposed thermocouples for each defect are given in Table 15. The extra thermocouples are those required beyond the base line test instrumentation.

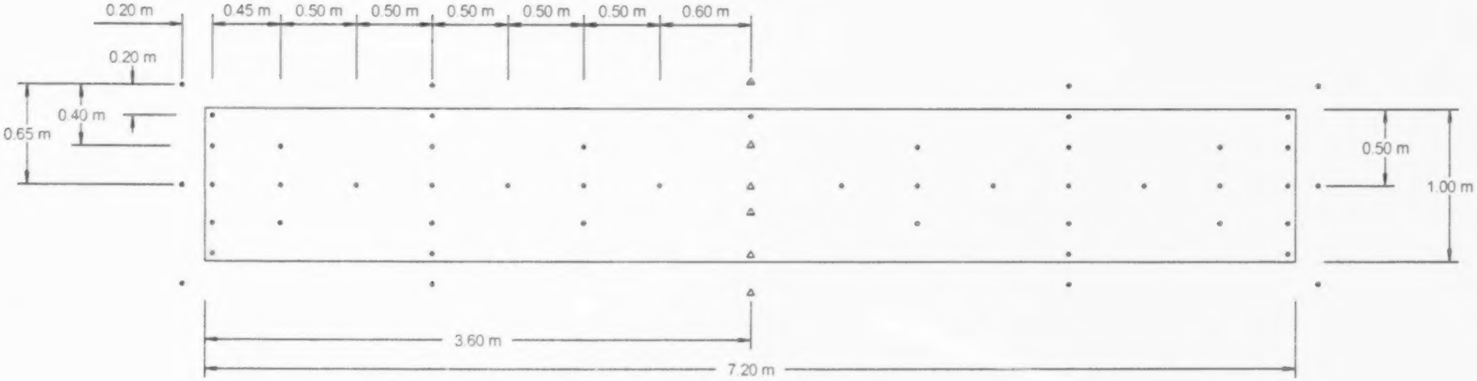
Table 15: Number of defect thermocouples

Defect	Total Thermocouples in Defect Area	Extra Thermocouples (Beyond Base Line Test)
Small axial	47	43
Medium axial	55	49
Small circumferential	42	28
Medium circumferential	48	34


0.20 m
0.45 m
0.50 m
0.50 m
0.50 m
0.50 m
0.50 m
0.60 m
0.20 m
0.40 m
0.25 m
0.50 m
3.60 m
7.20 m

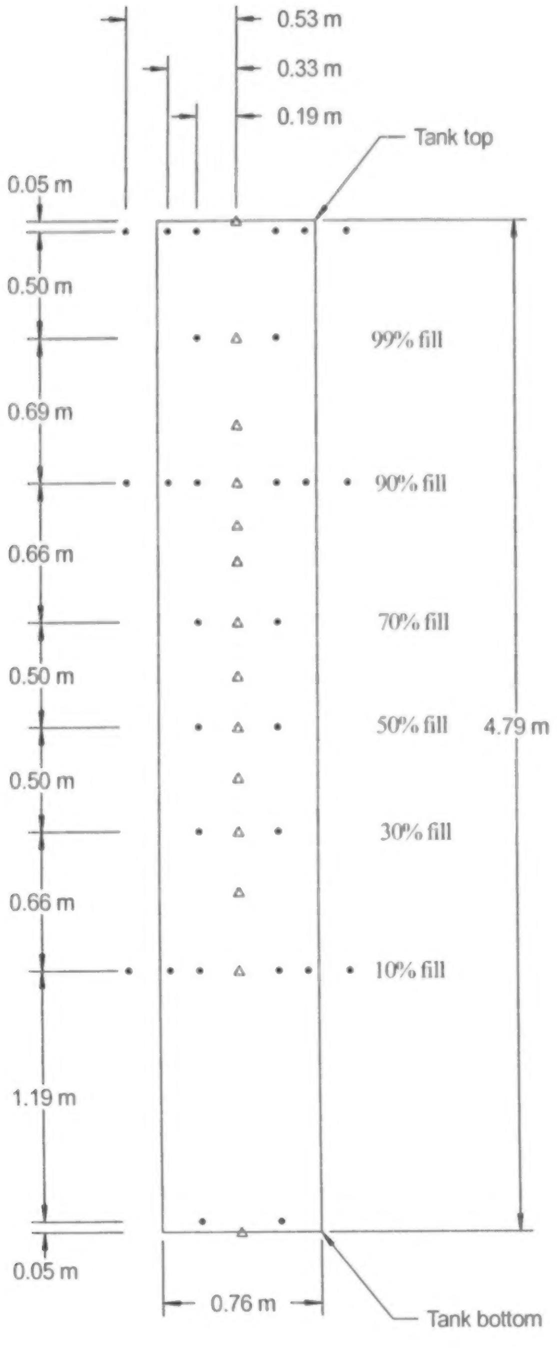
▵ Array wall thermocouples - vertical distances differ from specific defect thermocouples
• Defect wall thermocouples
Vertical center of defect is aligned with 90% fill level
Horizontal center of defect is aligned with thermocouple array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

Figure 28: Wall thermocouple locations for small axial defect


0.20 m
0.45 m
0.50 m
0.50 m
0.50 m
0.50 m
0.50 m
0.60 m
0.20 m
0.40 m
0.65 m
0.50 m
1.00 m
3.60 m
7.20 m

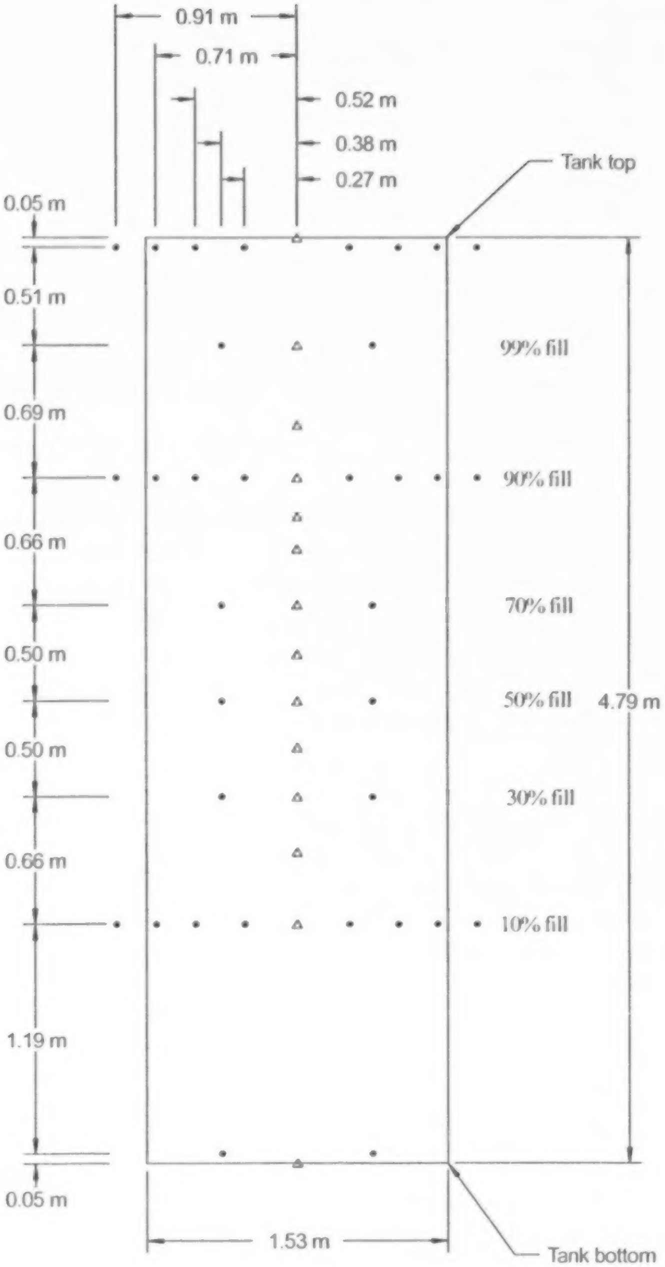
▵ Array wall thermocouples - vertical distances differ from specific defect thermocouples
• Defect wall thermocouples
Vertical center of defect is aligned with 90% fill level
Horizontal center of defect is aligned with thermocouple array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

Figure 29: Wall thermocouple locations for medium axial defect


0.53 m
0.33 m
0.19 m
Tank top
0.05 m
0.50 m
99% fill
0.69 m
90% fill
0.66 m
70% fill
0.50 m
50% fill
4.79 m
0.50 m
30% fill
0.66 m
10% fill
1.19 m
0.05 m
0.76 m
Tank bottom

△ Array wall thermocouples
• Defect wall thermocouples
Vertical length spans one side of tank (top to bottom)
Horizontal center of defect is aligned with array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

Figure 30: Wall thermocouple locations for small circumferential defect



0.91 m
0.71 m
0.52 m
0.38 m
0.27 m
Tank top
0.05 m
0.51 m
99% fill
0.69 m
90% fill
0.66 m
70% fill
0.50 m
50% fill
4.79 m
0.50 m
30% fill
0.66 m
10% fill
1.19 m
0.05 m
1.53 m
Tank bottom

△ Array wall thermocouples
• Defect wall thermocouples
Vertical length spans one side of tank (top to bottom)
Horizontal center of defect is aligned with array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

Figure 31: Wall thermocouple locations for medium circumferential defect

5.1.2. Summary

Table 16 provides the total number of thermocouples for each test. The number of lading, jacket and PRV thermocouples does not change with the addition of thermal defects, but additional wall thermocouples are required. The medium axial defect requires the most additional thermocouples, due to little matching between the defect thermocouples and existing wall thermocouples, resulting in the largest total number, 416. The other end of the range is the baseline test with 369 thermocouples.

This is a very large number of thermocouples and, if budget limitations require, it is possible to reduce the total number. However, care must be taken not to reduce the number too much because good temperature data is critical for this kind of testing. It should also be noted that during the tests data from several thermocouples will probably be lost or the data suspect. This could affect 10% of the readings.

The components for the thermocouples are given in Table 17. If a new tank-car is used and the thermocouples installed as it is built, the modifications to the tank-car will be minor. However, if old tank-cars are used the jacket and insulation will have to be removed in the vicinity of the wall thermocouples to allow installation. The jacket and insulation will also have to be removed to allow the wires to be routed back to the instrument well. Depending on the costs, if old tank-cars are used it may be worthwhile to remove all the old insulation and replace it with new. This will make installation of the exterior thermocouples easier, and provide consistent insulation with known properties, which is not the case for used.

In addition to the thermocouples, extension cable is required to communicate the signal to the instrument bunker. Heavy gauge wire must be used to cover the distance without excessive losses in the low voltage thermocouple signal. A 16 gauge wire 60 m long is required. This can be obtained with 24 pairs bundled into a cable, and 18 of these cables are required. The cables can be re-used for each test.

Table 16: Number of thermocouples required per test

Test Type	Location	No. of Probes	No. of Thermocouples	Total
Baseline	Lading	21	228	228
	Tank wall	N/A	94	94
	Jacket & PRV	N/A	47	47
	Total			**369**
Small Axial	Tank wall (beyond baseline)	N/A	43	137
	Total			**412**
Medium Axial	Tank wall (beyond baseline)	N/A	49	143
	Total			**416**
Small Circumferential	Tank wall (beyond baseline)	N/A	28	122
	Total			**395**
Medium Circumferential	Tank wall (beyond baseline)	N/A	34	128
	Total			**403**

Table 17: Thermocouples and accessories

Test Type	Part	Quantity
Baseline	Lading TC sets	3
	Tank feed throughs	7
	Array support frame	3
	Wall TCs	1
	Jacket & PRV TCs	1
Small Axial	Lading TC sets	3
	Tank feed throughs	7
	Array support frame	3
	Wall TCs	1
	Jacket & PRV TCs	1
Medium Axial	Lading TC sets	3
	Tank feed throughs	7
	Array support frame	3
	Wall TCs	1
	Jacket & PRV TCs	1
Small Circumferential	Lading TC sets	3
	Tank feed throughs	7
	Array support frame	3
	Wall TCs	1
	Jacket & PRV TCs	1
Medium Circumferential	Lading TC sets	3
	Tank feed throughs	7
	Array support frame	3
	Wall TCs	1
	Jacket & PRV TCs	1

5.2. Tank-Car Wall Strain

It may be desirable to measure strain in the tank car wall at some locations.

Measurement of elastic strain at many locations on the tank wall will add considerably to the cost of the testing. Current tank thermal models do not model the stress and strain field in 3-dimensions, or even 2-dimensions, they consider hoop stress only. This means local measurement of strain is of little value for current tank thermal models.

It may be desirable to include some instrumentation in the area of the thermal protection defect to sense large scale strain. The challenge is that this region will get very hot and may suffer large scale plastic deformation. However, it may be possible to incorporate simple on/off devices that indicate thresholds of plastic deformation. This could provide valuable real time data to the test operators.

No stain instruments are included in this plan.

5.3. Tank-Car Pressure

Pressure is a critical parameter, in data analysis and test safety, so multiple redundancies are provided. Four pressure sensors are connected to the tank-car. The vapour vent line transducer is connected to the vapour vent line just before the remote control valve. This removes the transducer and wiring from the pool fire entirely. The pressure range on this transducer is specified as 6900 kPaG (1000 PSIG), for the unlikely event of the PRV valve sticking beyond 3450 kPaG (500 PSIG). The remaining transducers have a maximum 3450 kPaG (500 PSIG) range, which is the most likely upper limit on pressure and provides increased accuracy compared to the 6900 kPaG (1000 PSIG) range. The liquid drain line transducer is connected just before the remote valve on the liquid drain line, again removing the transducer from the pool fire. The location of these transducers will also indicate if the valves have opened during the abort procedures. This will be useful, since with the distances involved visual verification may be difficult.

The two remaining transducers are located in the connection well, at the bottom of the instrument well. 0.6 cm (¼ inch) stainless steel tube connects the bottom of the tank-car to the transducer. One of the transducers is connected, via stainless steel tube inside the tank-car, to the vapour space near the PRV. This should provide an indication of when the PRV is open, and if it has stuck open during the test. Table 18 summarises the proposed pressure transducers. In addition a power supply is required that can provide between 10 and 30 Vdc.

The vapour vent line transducer will also be connected to the control bunker as a backup if the data acquisition system fails. A 24 V power supply will be required in the bunker and a voltmeter to measure the voltage. A plot of the voltage pressure correlation for the system will also be available. The termination of the wires in the control bunker will not be connected to the power supply, or voltmeter, unless the data acquisition system fails.

Table 18: Pressure transducer locations and specifications

Location	P/N (Omega)	Range (kPa)	Accuracy (kPa)
Vapour Vent Line	PX615-1KGI	0-6900	± 28
Liquid Drain Line	PX615-500GI	0-3450	± 14
Transducer Well	PX615-500GI	0-3450	± 14
Transducer Well - PRV	PX615-500GI	0-3450	± 14

5.4. Tank-Car Fill Level

The saturated conditions, with elevated temperature and pressure, inside the tank-car make continuous monitoring of the fill level difficult. The conditions at the liquid vapour interface, particularly when the PRV is open, also complicate level determination. Liquid frothing at the interface and local swelling challenge all level sensors, resulting in an estimate of the depth, often with unknown error.

Fill level sensors, which function without a probe extending into the liquid, rely on bouncing ultrasonic or radar waves off the liquid surface, and need to be mounted at the tank-car top. They are available with the required range for a large tank-car, but the electronics limit the temperature to about 100°C. This will be far exceeded at the top of the tank-car, both in the vapour space and on the wall. The sensor type would not be able to survive the test.

Capacitance probes detect the change in capacitance when the liquid/vapour interface passes. They have a higher temperature range than the remote probes, up to 200°C. Their disadvantages include: not being available in the length required to measure the full tank-car height, and giving false readings if they remain wet above the liquid level. With frothing occurring and the presence of a saturated vapour this could result in serious errors. The cost of this type of probe is approximately twice that of the ultrasonic sensors.

Multiple point level measurement devices are available that can be mounted on the bottom of the tank-car. The floats can survive up to 150°C and their destruction after emerging from the liquid would not matter. However, this system would provide no more information than estimating the level from the thermocouple readings. The floats would be susceptible to frothing and swell in the tank-car.

Measurement of the liquid head can be used to determine the depth. Since the tank-car is pressurised the low pressure measurement has to be taken in the vapour, and, due to the saturated state of the propane, it could condense in the connecting tube making the result meaningless.

The weight of the rail tank-car and propane could also be used to determine the fill level. The cost for 8 load cells, 4 for each rail tank-car support, would be approximately four times that of the capacitance probes. The load cells are good up to 165°C and could be installed near the bottom of the fire pan, which is always immersed in water. It would also be necessary to subtract out the PRV thrust if the level was required while the tank was venting. The disadvantage of this technique is cost.

The installation of a liquid depth gauge is not worth the cost and effort to install it. The available gauges that provide more information than the thermocouples cannot withstand the harsh environment they will be subjected to, or deal with the surface conditions. The weight of the rail tank-car could be used to determine fill level. The installation of a camera inside the tank-car, however, would provide valuable information on the behaviour inside the tank-car, and an estimate of the fill level. It is unlikely that the camera would survive the entire test, but any length of recording would produce unique data and insight into the propane behaviour.

The camera will be placed inside a 15.2 cm (6 inch) NPT pipe with a window attached at one end and a plug at the other, drilled and tapped to accept the feed throughs for the power and video cables. The housing will be pressure tight to protect the camera and prevent leaks through the cable. Two stainless steel clad, 2 conductor, cables are required, one to carry the video signal and the second to supply the power. The stainless steel cables terminate in the connection well and connect to a coaxial cable, for the video signal, and a 2 conductor wire, for the power. The outside of the tube will be insulated to delay the heating of the camera. In addition, extra space in the housing will be filled with steel, to act as a heat sink, further extending the life of the camera. The required components are given in Table 19.

The camera incorporates light emitting diodes (LEDs) to illuminate the tank-car, and the image will be recorded on a DVD recorder in the instrument bunker. The camera will be placed near the top of the tank-car so that it will be able to view the surface of the liquid when the fill level is 95%. It will be angled down so that it can continue to see the surface as it empties. A pole with marked fill levels should be installed in the field of view to allow more accurate determination of fill level. One of the thermocouple array frames could be used for this purpose.

Table 19: Internal video camera system components

Component	Part Number	Quantity
Components Required for Each Test		
Camera	Micro-Video MVC2120-WP	1
Housing	Custom	1
Feed throughs	Omega MFT-14-3	2
Stainless steel clad wire	Omega Special order	2
Components Re-Used for Every Test		
Power cable		1
Coaxial cable		1
DVD recorder		1

6. Pool Fire Instrumentation

It is essential that the properties of the pool fire be well documented. This will be critical data for model development and validation. The following features of the pool fire should be recorded.

i) time varying temperatures
ii) time varying heat fluxes in fire
iii) variation in heating along tank length
iv) fire shape over the test duration
v) tank engulfment conditions

Large, open pool fires do not have constant properties. The temperature and shape fluctuate with time. Engulfment of objects is intermittent. Wind has strong affects on these properties. This is all expected due to the turbulent structures in such a fire. However, it must all be measured if we want to specify a design case fire condition.

The temperature changes across the width, length and height of the fire. The temperature profile changes from test to test, and even within tests, due to variations in wind speed and direction, and due to the transient nature of the fire during ignition. Local geography also affects the conditions altering how air is drawn in. Even the presence of the large, cold tank-car, will alter the temperature. Variations due to wind and geography can be reduced, but not eliminated. Although it is hoped that the fire temperature will be in the specified range (871°C ±56°C) it cannot be guaranteed because a pool fire has no control parameter.

6.1. Fire Temperature

The fire temperature will be measured with K-type thermocouples, with 0.3 cm (1/8 inch) probe diameter, with super omega clad sheathing. The probe tip will be unshielded to enhance the response time. This measures the perceived temperature at that point including radiation to the cool surroundings and hot fire, and convective heat transfer from the combustion gases. These are simple, easy to install, rugged and relatively inexpensive.

For more precise characterisation DFTs will be used. These measure the temperature in one direction only. They are a thermocouple mounted on the back of a stainless steel plate, followed by a small air gap and insulation. The thermocouple reads the blackbody temperature of the fire that the plate is exposed to (Koski et al). The DFT, presented in Figure 32, is based on the design of Koski et al., but modified to work in four directions. The locations of the simple thermocouples and DFTs are shown in Figure 33.

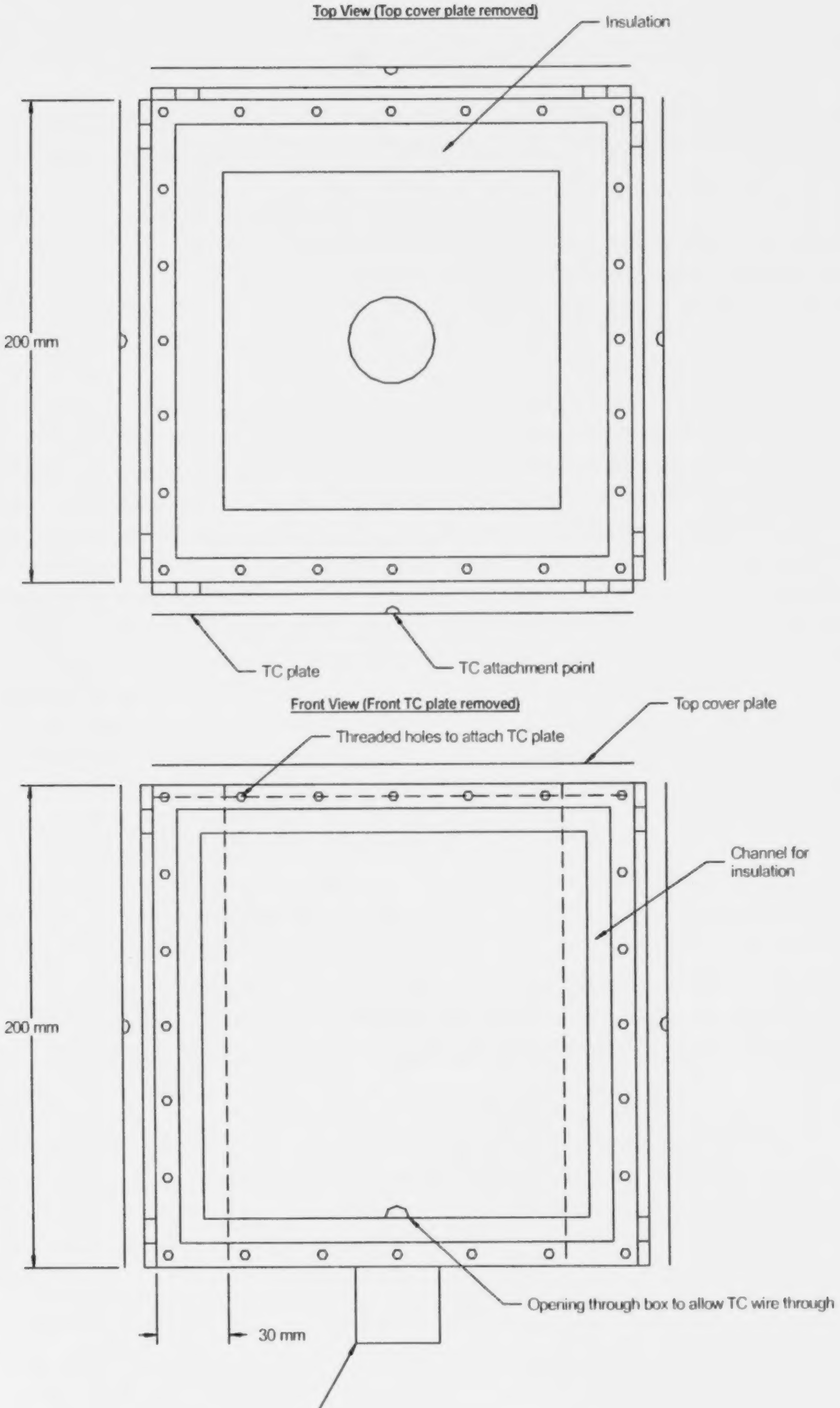
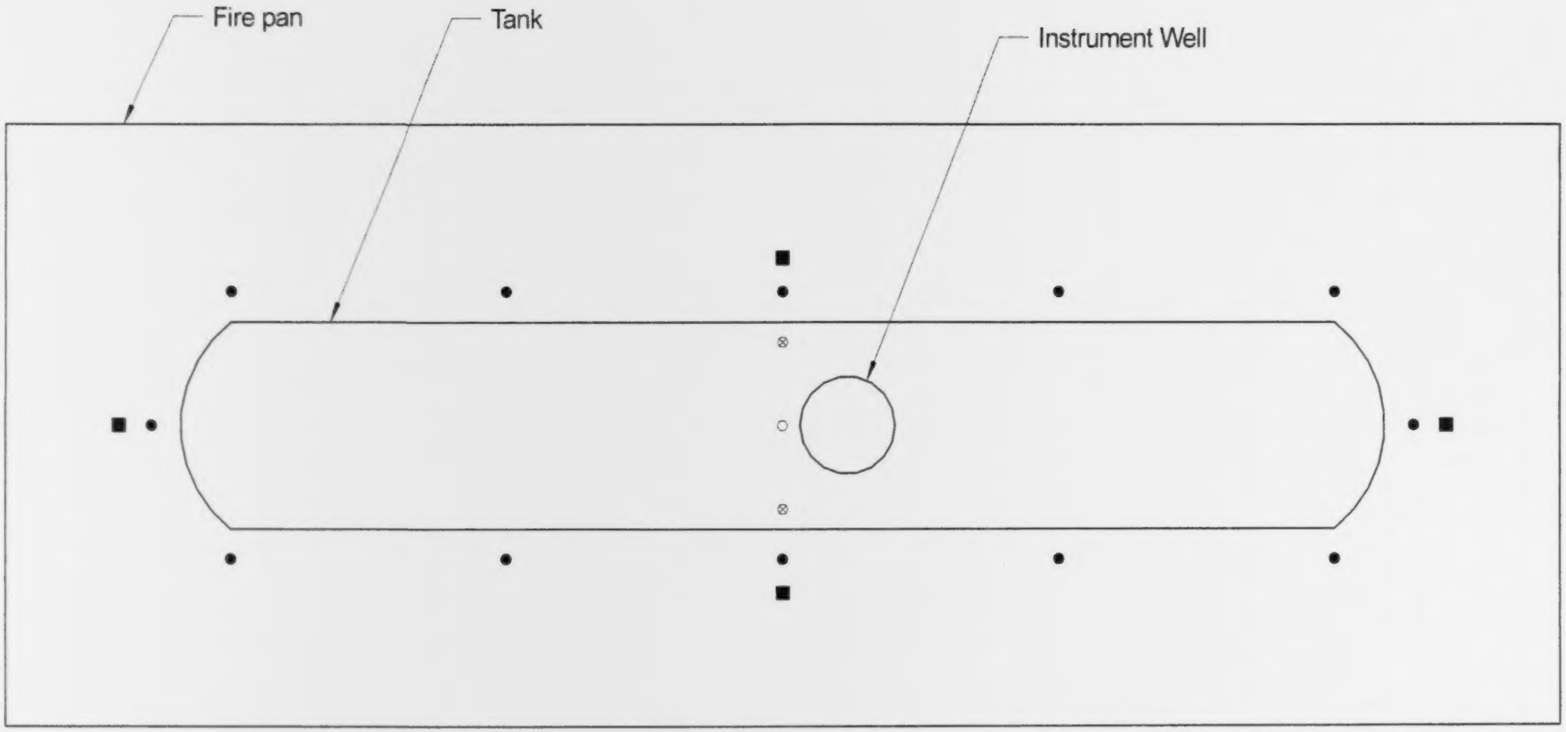

Top View (Top cover plate removed)
Insulation
200 mm
TC plate
TC attachment point
Front View (Front TC plate removed)
Top cover plate
Threaded holes to attach TC plate
Channel for insulation
200 mm
Opening through box to allow TC wire through
30 mm
1" NPT coupling for routing TC wires

Figure 32: Drawing of DFT


Fire pan
Tank
Instrument Well

● Fire TC located at elevation aligned with tank midline
○ Fire TC located at elevation over top of tank
⊗ Fire TC located at elevation aligned with tank bottom
■ DFT located at elevation aligned with tank midline

Figure 33: Locations of fire thermocouples and DFTs

The thermocouples are concentrated around the tank-car, since that is the area of interest for the test. If funds are available to add more thermocouples, additional elevations should be included. However, the fire temperature at other locations and elevations can also be estimated from the jacket thermocouples, which are attached to a relatively thin steel jacket exposed to the fire and backed with insulation. Some thermocouples may require replacing after each test, but most will survive. The DFTs should withstand all tests and if the thermocouple wire fails it will likely only require re-welding to the plate.

6.2. Fire Heat Flux

Heat flux is determined by both the conditions of the fire and the properties of the surface the heat is being transferred to. Commercial heat flux sensors are designed to be attached to a surface, and measure the temperature difference across the sensor to determine the heat transfer. If the jacket and wall thermocouples are aligned radially on the tank-car the heat flux could be determined from the measured temperatures and the properties of the insulation.

Heat flux sensors, independent of the tank-car, can quantify the fire conditions for comparison to other locations in the fire and between each of the tests. The heat flux sensor should meet the following criteria:

1. Rugged – must be able to survive all tests if tank-car does not fail.
2. Cost effective – since the objective is only comparative excessive cost to achieve high accuracy is not required.
3. Repeatable – results must not change with time.

A simple water piping system with thermocouples situated along the centre axis meets these criteria. It will be constructed of schedule 40 black pipe and should survive all four tests. A thermocouple profile probe will be inserted along the centre of the pipe. The most problematic aspect of the calorimeter is mixing the water prior to the thermocouple elements. This is required to disturb the thermal boundary layer and obtain the mean temperature of the water. Mixing will be achieved by expansion and contraction using standard pipe fittings. The construction will have to be tested, prior to the field work, to ensure adequate mixing. Since only the pipe is exposed to the fire, and it is water cooled, the system should withstand multiple tests. Even if the system runs dry during the test the system will survive. The thermocouples are rated to the fire temperature, and the piping is low pressure so any reduction in the steel properties will not be a problem.

Fresh water will be continuously pumped into the instrument at the same flow rate and initial temperature, reducing changes in results with time. The effect of sooting on the pipe will alter the heat transfer, but this should occur quickly in the first pre-test burn, and any soot lost during preparation for subsequent tests will quickly be replaced in the early stages of the each fire. The flow and heat transfer in the calorimeter is given below. This is a worst case scenario for heat transfer, ensuring that the water will not boil in the instrument.

T_{fire} = 1027°C
T_{in} = 20°C
T_{out} = 90°C
Calorimeter view factor to fire = 1
Heat transfer = 220kW
Flow rate = 0.75 kg/s

Figure 34 is a schematic of the calorimeter. A 38,000L (10,000 gallon) water supply tank, 25 m from the fire pan, will be needed to supply all 3 meters. Earth will be piled around the sides and over the top to reduce heat transfer from the pool fire.

For each calorimeter a pump moves the water through the system and is followed by a flow meter. The flow meter system is made up of a turbine flow meter, signal conditioner and thermocouple. A ball valve is used to control the flow rate and equalise it in each calorimeter. The ball valves are manual and will be set prior to the test. The section over the fire pan is made up of 9 single calorimeter sections, shown in Figure 35. The temperature is measured with a profile temperature probe inserted through the calorimeter sections. This allows the width of the fire pan to be broken into 9 zones and the heat transfer in each zone assessed. A support will have to be welded into each 7.6 cm (3 inch) short nipple to hold the probe in the centre of the pipe. To further enhance mixing the support will be constructed of square pieces to enhance flow separation. The installation of expanded metal in the fittings would also increase mixing. The calorimeter components are summarised in Table 20. Three calorimeters will be distributed along the length of the tank-car, one at either end, under the elliptical heads, and one in the centre.

The pumps and flow meters will be located behind the water tank. This will maximize the distance from the pool fire. A cover will extend out beyond the water tank to shield the pumps from thermal radiation from the pool fire. The top will be covered with earth, but the back and sides left open to allow air flow through the shelter. The water flowing through the pump and flow meter should adequately cool them, but a fan may be required to enhance cooling of the pump motors. The piping to the fire pan will be buried to reduce the heating of the water before it reaches the fire.

Table 20: Calorimeter components

Component	**Qty./Meter**	**Total Qty.**
Pump (24 US gallons per min.@10 ft. head, 1/3HP)	1	3
Flow meter system (meter, signal cond., TC)	1	3
Cable (4 conductor, 24ga, copper) for flow meter	1	3
Piping	1	3
Profile probe	1	3
Thermocouple extension cable (16ga, 24 pair)	2/3	2
Calorimeter sections	9	27
Water supply tank	1/3	1

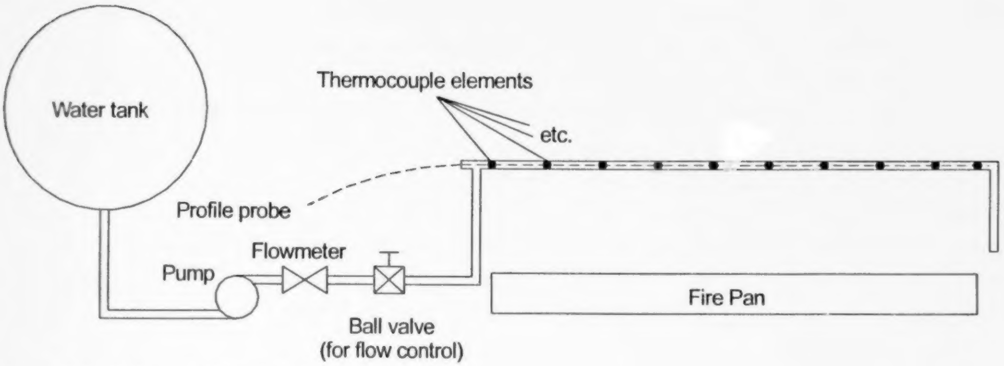

Water tank
Thermocouple elements
etc.
Profile probe
Flowmeter
Pump
Fire Pan
Ball valve
(for flow control)

Figure 34: Schematic of calorimeter setup

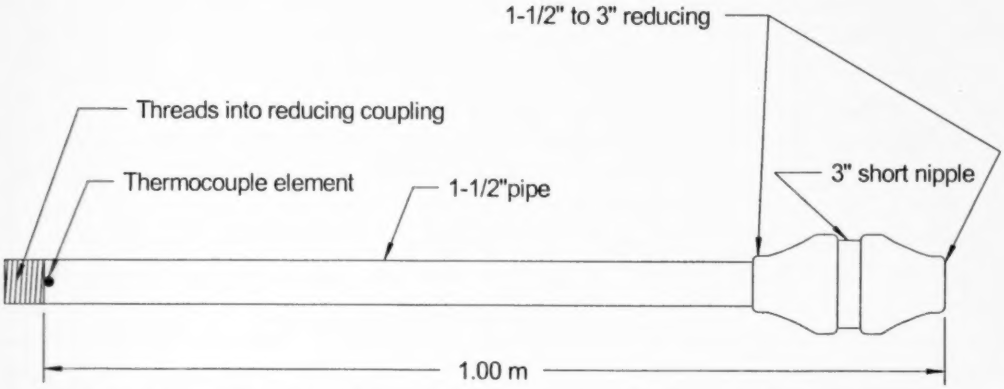

1-1/2" to 3" reducing
Threads into reducing coupling
Thermocouple element
1-1/2"pipe
3" short nipple
1.00 m

Figure 35: Single calorimeter element (9 elements make up calorimeter)

7. Field and High-Speed Instrumentation

The field instrumentation is not installed in either the test tank-car or fire pan. It captures a larger sample of the pool fire conditions, monitors weather conditions and captures thermal and blast data. Due to the similarity of high-speed pressure transducers and blast gauges, and the fact that they share signal conditioners, all the high-speed pressure instrumentation is included in this section.

7.1. Weather Conditions

As discussed in section 4.2, wind strongly affects the pool fire and heat transfer to the tank-car. The tank will be installed with the long axis aligned with the prevailing wind direction, and tests will be performed when the wind is at a minimum. Wind monitoring stations will be set up as early as possible during the site preparation, so a database of daily wind patterns can be produced. This database can be used to determine the expected conditions and the optimal time of day to perform the test, and will be used in conjunction with the weather forecasts for the area. The test time will likely be early in the morning or late in the afternoon when the sun is generating less thermal effects. A good record of wind conditions during the test is also required and may help explain any anomalous outcomes. Historical weather data should also be consulted to determine the prevailing wind direction to establish the tank orientation.

Three weather stations are proposed. The first, located at the control bunker, records the following:

- Wind speed
- Wind direction
- Temperature
- Humidity
- Barometric pressure

This is a self contained system with a digital display and computer interface for data recording. It can be connected to any laptop or PC with a serial connection port. It is not recommended that it be connected to the computer acting as a terminal for the data acquisition and control computer, but any other, less critically occupied, computer could be used.

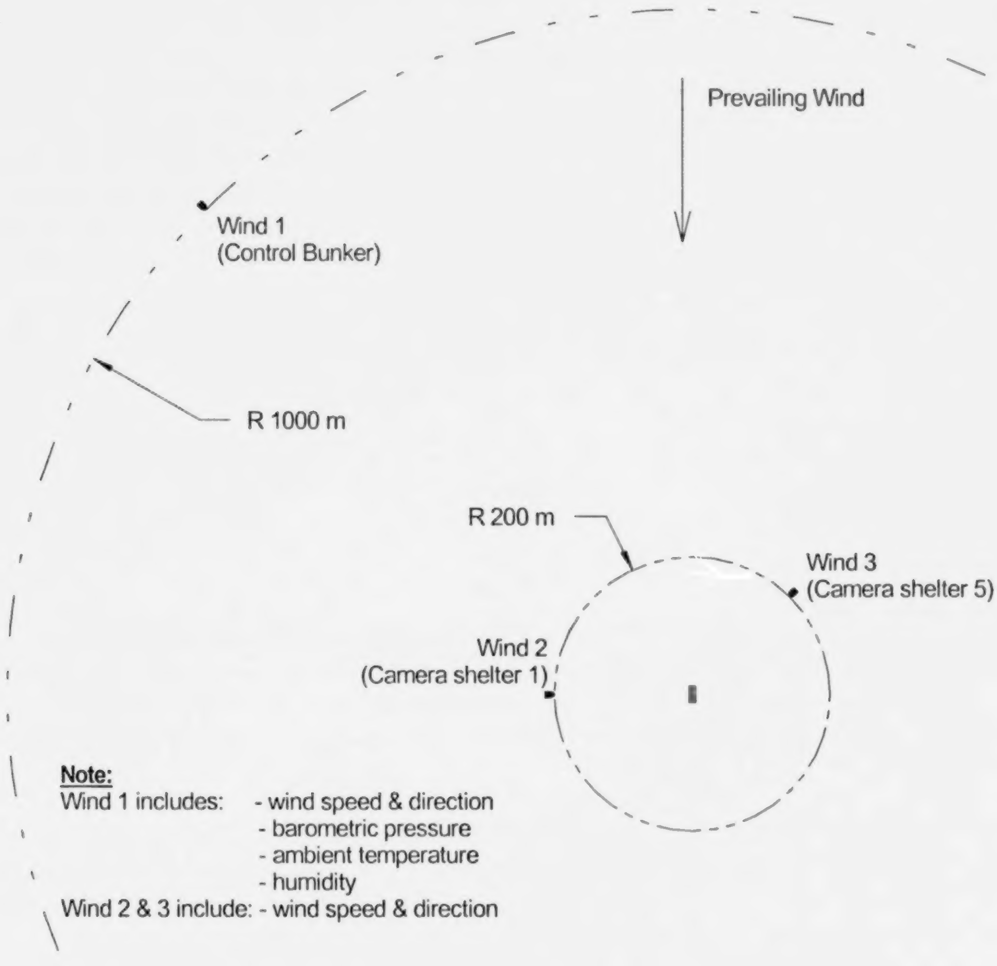
The remaining two stations are located at the 200 m distant camera shelters, as shown in Figure 36. The distance will reduce the effects of the draw created by the pool fire, and prevent damage to the instruments by thermal radiation. They will likely survive a tank-car failure at this distance. These two weather stations record the following:

- Wind speed
- Wind direction

They produce two 4-20 mA outputs representing wind speed and direction. These signals will be fed into the data acquisition system in the instrument bunker for recording and monitoring. The weather instrumentation is summarised in Table 21.

Table 21: Weather station components

Location	Components
Control bunker	Davis Weather Monitor II
	Davis External humidity sensor
	Weather link
Video 1 camera shelter	Omega WMS-22B Wind Sensor
	6 Conductor cable
Video 5 camera shelter	Omega WMS-22B Wind Sensor
	6 Conductor cable


Prevailing Wind
Wind 1
(Control Bunker)
R 1000 m
R 200 m
Wind 3
(Camera shelter 5)
Wind 2
(Camera shelter 1)

Note:
Wind 1 includes:
- wind speed & direction
- barometric pressure
- ambient temperature
- humidity

Wind 2 & 3 include:
- wind speed & direction

Figure 36: Location of weather stations

7.2. Blast Gauges and Transient Tank-Car Pressure

7.2.1. Blast Gauges

In the event of a tank failure it would be very desirable to measure hazards due to the blast and thermal radiation from the fireball. Very little detailed data is available on hazards from this size of tank.

Blast gauges are positioned along the tank-car centre lines to measure the over pressure caused by an explosive failure. Gauges are proposed at distances of 25, 50, 100 and 150 m along the radial and axial centre lines. The layout is shown in Figure 38. B9, B10, B11 and B12 are added to verify the symmetry of the blast. The expected overpressure, calculated as per the BAM report on their rail tank-car testing (Balke et al., 1999), is plotted in Figure 37. The proposed blast gauge range is up to 345 kPaG, which should be adequate even for the 25 m distant gauges. At 25 m a 65 kPa overpressure is calculated, which can be out by a factor of 5 and still be within the gauge range.

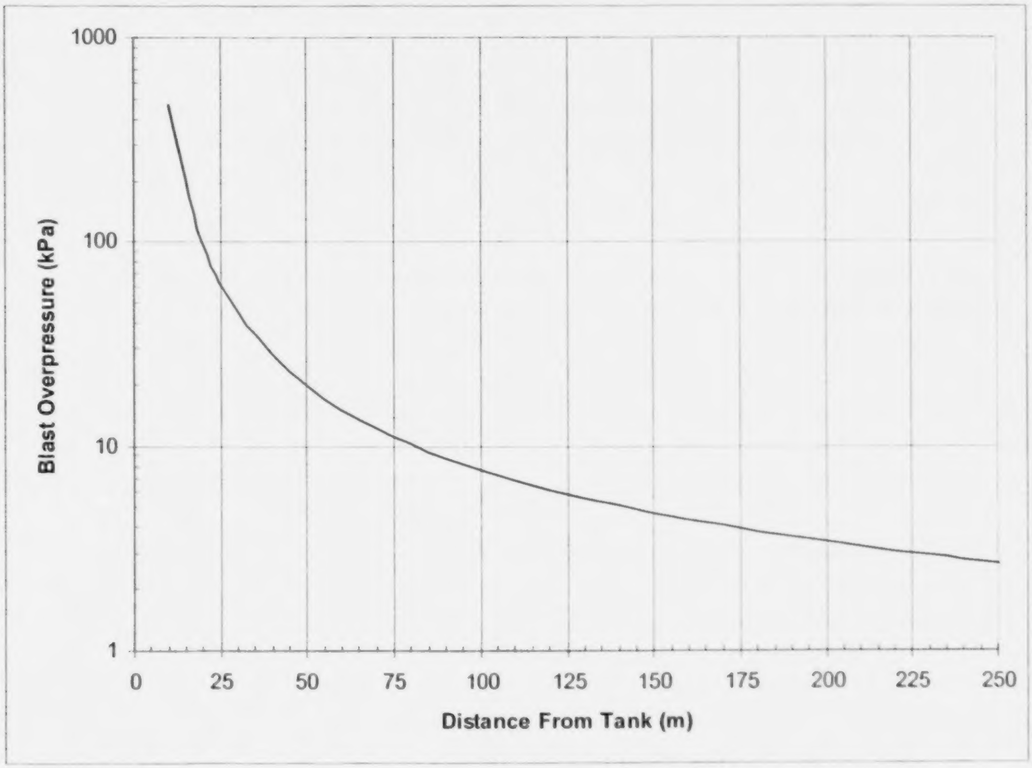


Figure 37: Blast overpressure from tank-car failure with distance from blast

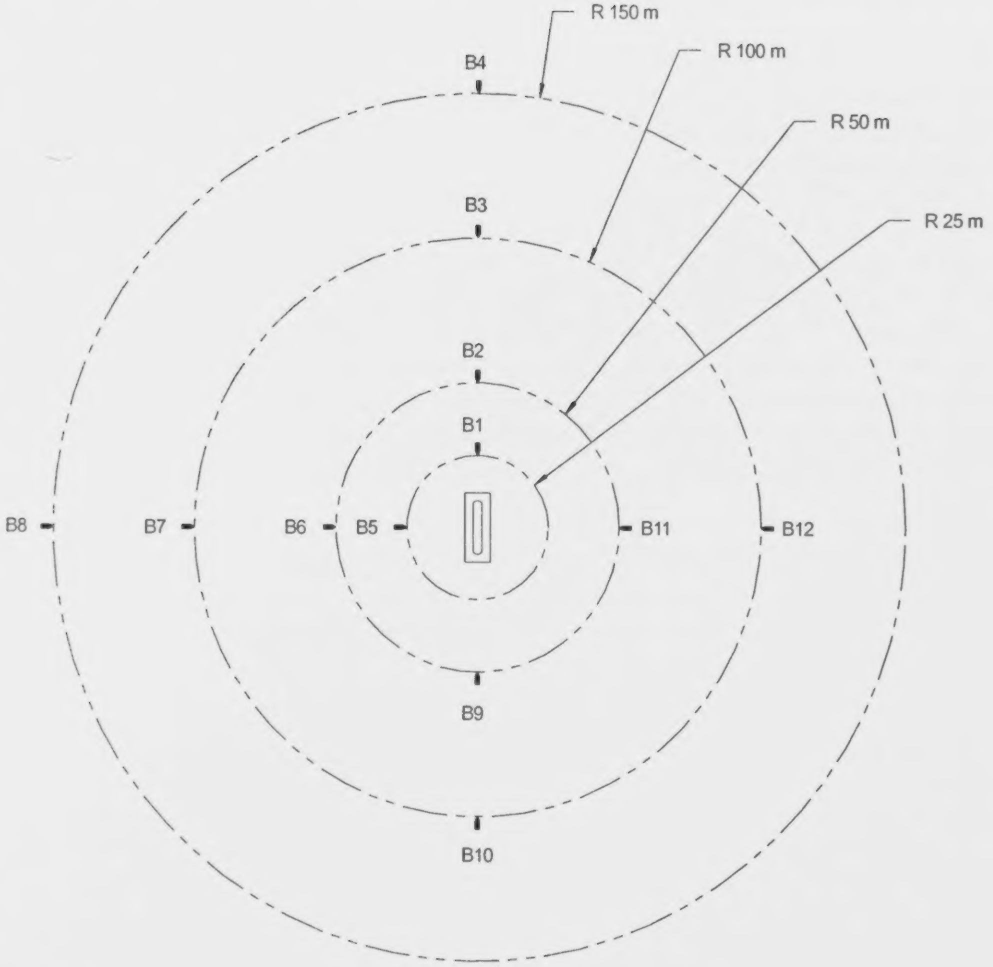


Figure 38: Location of blast gauges relative to tank-car centre

The blast gauges positioned at the 25 and 50 m radii will have to be shielded from the pool fire radiation. Aluminium foil will shield from the thermal radiation, but should allow the blast wave to pass through. Depending on wind condition this may not be adequate to preserve the gauges at the 25 m or 50 m radii on the downwind side. During the pre-test burn inoperable or mock blast gauges will be installed at the locations near the pool fire and the temperature monitored during the test. Final placement and cooling of the gauges will be modified based on these results.

7.2.2. Transient Tank-Car Pressure

A high-speed pressure transducer is included on the tank-car to capture any high-speed pressure transients. For example, during PRV opening or tank failure.

The transient pressure transducer has the same principle of operation as the blast gauges, and can be connected to the same power supply/signal conditioner. The high-speed transducer only measures rapid changes in pressure. To follow the tank-car pressure a standard pressure transducer will be connected to the high-speed acquisition system, in addition to the slow-speed DAC. This allows medium speed transients (such as PRV activation) to be easily followed and analysed. It also provides a trace of the test making the high-speed transients easier to locate.

The high-speed transducer will capture any interesting pressure responses due to the relief valve opening. The slow-speed transducer will provide a marker for the opening of the relief valve, allowing the transient to be quickly identified and distinguished from spurious signals. The standard pressure transducer has a response time of 5 ms, which is fast enough to capture some of the transient pressure responses without the high-speed transducer.

To mount the high-speed transducer, a ¾ inch plug will have to be drilled and tapped with a $^3/_8$-24 thread. The modified plug is screwed into a fitting on the tank-car and the sensor into the plug. The plug and sensor will have to be covered with insulation to maintain it below its operating limit of 135°C. The tank-car walls in the instrument well will remain below 70°C, so the sensor will be well within its operating limits. High temperature wire will have to be used to connect the sensor to the initial signal conditioner in the connection well.

7.2.3. Cables and Signal Conditioning

The long lengths of cable required can result in loss of transient data by filtering out higher frequencies. Increasing the current supplied to the sensor increases the allowable length of cable, but high currents on short lengths can result in sensor overheating, especially in high ambient temperatures. Lower capacitance cables also increase the frequency of data that can be transmitted. Using 2 signal conditioners allows for the near and far sensors to be grouped and fed with different currents. Lower voltage signals also result in higher frequency response.

Table 22 gives the proposed current to each sensor and the corresponding frequency that can be transmitted through a cable with a capacitance of 44.4 picofarads/m (13.5 picofarads/ft.). It gives the frequency for the maximum voltage of the sensor, 5 V, and the maximum voltage expected from the blast gauges, 2V. As the blast gauge is positioned further away it requires a longer cable, but will sense a smaller overpressure resulting in a lower signal voltage, which increases the transmissible frequency. The signal conditioner has an adjustable current output with a 20 mA maximum.

Table 22: Transmissible frequency through RG62A/U coaxial cable with 5 V maximum signal and 2 V maximum expected signal

Sensor	Cable Length (m)	Cable Capacitance (Picofarrads)	Supply Current (mA)	Transmissible Frequency (kHz)	
				5 V	2 V
B1	70	3,100	5	41	102
B2	80	3,550	5	36	89
B3	125	5,550	12	63	158
B4	170	7,550	12	46	116
B5	30	1,330	5	96	239
B6	10	440	5	287	717
B7	60	2,660	5	48	120
B8	90	4,000	5	32	80
B9	80	3,550	5	36	90
B10	170	7,550	12	46	116
B11	150	6,660	12	53	132
B12	250	11,100	12	32	79
Pressure	60	2,660	12	130	330

7.2.4. Data Acquisition and Summary

The high-speed data can be recorded on a PC based data acquisition system. The National Instruments DT3010-268 DAC card can continuously acquire data at a total frequency of 1.25 MHz. With 14 channels this results in 89 kHz per channel, For a 100 minute test it will produce 42 gigabytes (Gb) of data. For comparison, an hour of uncompressed video is 15 Gb. If higher frequency acquisition rates are desired for the transient pressure a second board could be installed. The use of higher frequency data acquisition rates would have to be considered in consultation with the results in Table 22. Recording at higher frequencies than can be transmitted will not harm the system, but is a waste of resources. The high-speed instruments are summarised in Table 23.

Table 23: Transient pressure and blast gauge specifications

Instrument	P/N (PCB)	Range (kPa)	Qty.
Blast pressure pencil probe	137A23	±345	12
High-speed pressure sensor	101A02	±34,500	1
Signal Conditioner	498A02	N/A	2

Note: - Low-speed pressure sensor is specified in pressure section

7.3. Radiometers

Radiometers measure the infrared energy within their field of view. Common, and relatively inexpensive, versions are used to measure the temperature of an object. They assume an emmissivity of the object and adjust for the temperature of the radiometer to result in the objects temperature.

Radiometers are proposed to assess the pool fire and, if the tank-car fails, to assess the fire ball. Radiometers will be positioned as shown in Figure 39. Radiometers R1 and R4 are positioned to assess the pool fire temperature at the midpoint of the tank-car. Figure 40 shows the field of view for radiometer R1 at the edge of the fire pan where it will sense the fire temperature. The tank-car is shown for reference, although it will be obscured by the flame. Figure 41 is the field of view at the edge of the fire pan for radiometer R4. These radiometers have a 6° field of view, which is a 10:1 ratio of distance from radiometer to field of view diameter. The radiometers will require accurate positioning to achieve the desired field of view. A radiation shield will be required to shield the radiometer body from the pool fire and water cooling may also have to be considered. If the tank-car fails radiometers R1 and R4 will likely be destroyed.

The remaining radiometers are positioned to assess the fireball from tank-car failure. They have a 60° field of view and will be positioned with an upward angle of 25°. This minimizes the ground area in the view, but allows a large portion of the fireballs base to be captured. This orientation produces a field of view with a 210 m diameter for R2 and R5, and a 315 m for R3 and R6. This assumes the plane of the field of view passes through the ground at the centre of the test site and is 25° off vertical towards the radiometer. Figure 42 shows the approximate view of the fireball, produced by a 95% and 20% full tank-car. This view depends on the geometry of the fireball, which changes with time. It assumes a fireball height 3 times its radius, which was observed in the full-scale BAM tests.

The radiometers produce a K-type thermocouple output. Due to the long cable length transmitters will be required at most of the radiometer locations. This will convert the signal to a 4-20 mA output allowing it to be transmitted with little loss of accuracy. Table 24 summarises the required radiometers, their positions, and transmitter requirements.

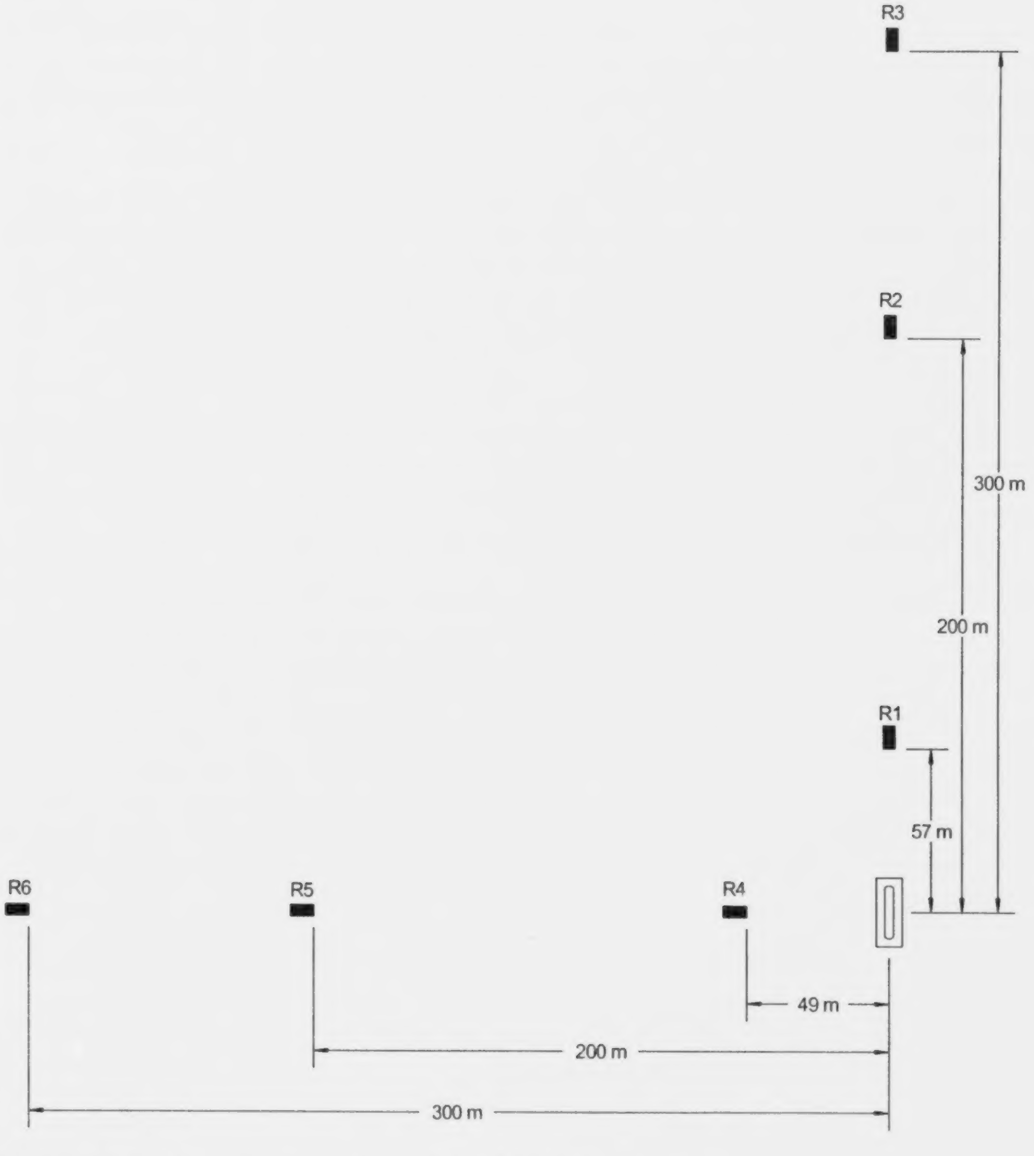

R3
R2
300 m
200 m
R1
57 m
R6
R5
R4
49 m
200 m
300 m

Figure 39: Radiometer locations referred to tank-car centre

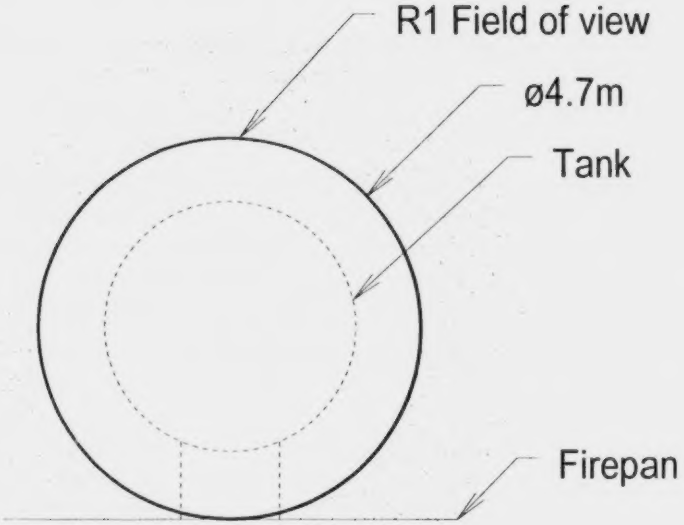

R1 Field of view
ø4.7m
Tank
Firepan

Figure 40: R1 Field of view at edge of fire pan with tank-car shown for reference

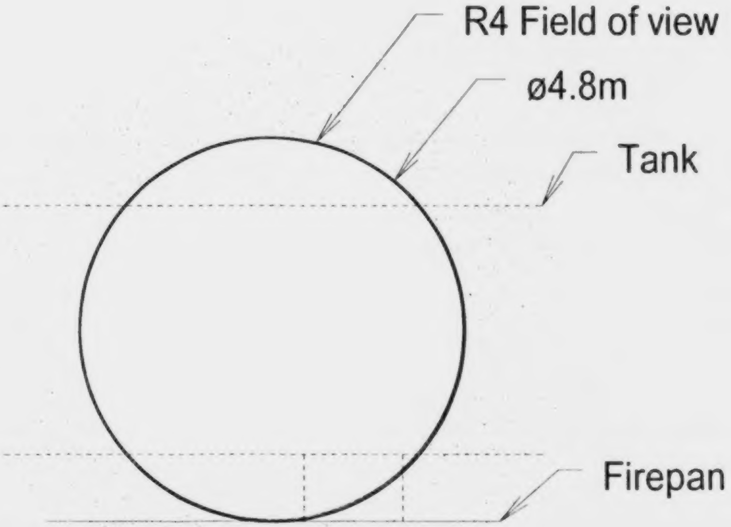

R4 Field of view
ø4.8m
Tank
Firepan

Figure 41: R4 Field of view at edge of fire pan with tank-car shown for reference

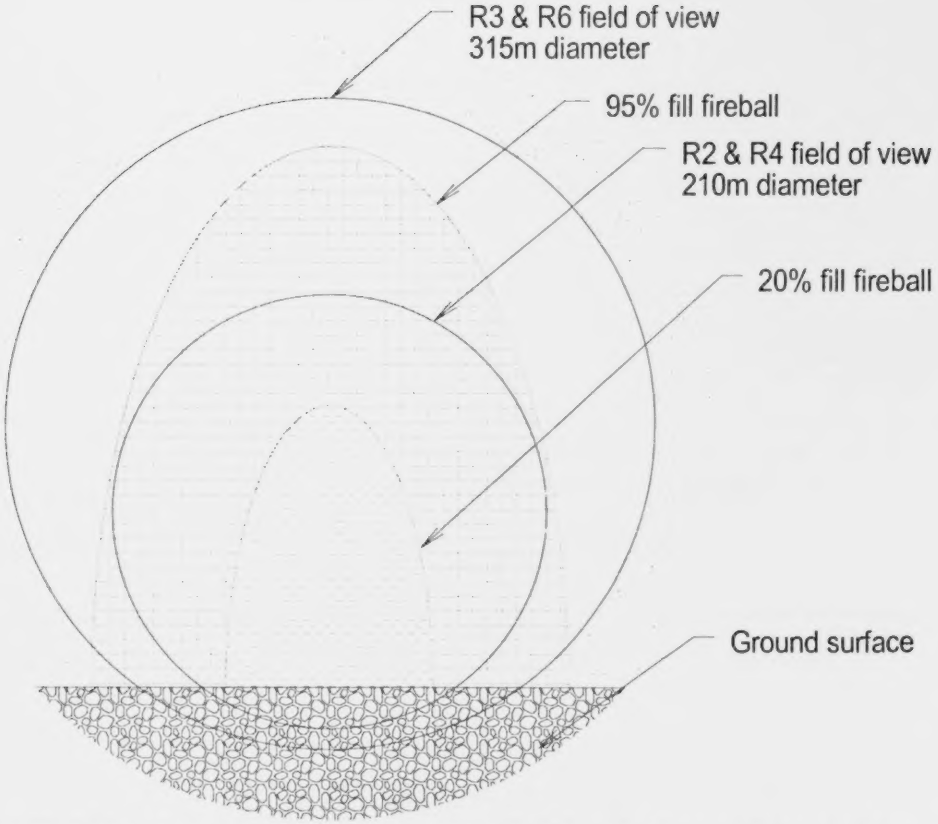

R3 & R6 field of view
315m diameter
95% fill fireball
R2 & R4 field of view
210m diameter
20% fill fireball
Ground surface

Figure 42: Field of view for radiometers R2, R3, R5 and R6 on a plane passing through the centre of the test site with radiometers on a 25° upward angle

Table 24: Radiometer locations and specifications

Location	P/N (Omega)	Transmitter P/N (Omega)
Axial, 57 m (R1)	OS36-10-K-440F	STCTX-K3
Axial, 200 m (R2)	OS36-K-440F	STCTX-K3
Axial, 300 m (R3)	OS36-K-440F	STCTX-K3
Radial, 50 m (R4)	OS36-10-K-440F	-
Radial, 200 m (R5)	OS36-K-440F	STCTX-K3
Radial, 300 m (R6)	OS36-K-440F	STCTX-K3

Notes: R4 requires K-type TC cable and the remainder 2 conductor shielded copper cable

8. Field Cameras

Field cameras will be used to make a visual record of the test.

This section covers the recommended video, still and high-speed cameras located external to the tank-car. The camera located internal to the tank-car, to help determine fill level and propane behaviour, is discussed in section 5.4. The field cameras role is to capture the behaviour of the pool fire during the test. If unusual data is obtained from the tank-car or pool fire sensors, the video cameras will provide a visual explanation. The still cameras provide instantaneous high resolution images of interesting events during the test.

The cameras also serve to capture tank-car failure, if it should occur. The video and still cameras provide images of the propane release and fireball over the entire duration of the failure. This can be analysed to determine fireball size and duration. The high-speed camera captures a short period of time about the failure in small time steps. This can be used to determine how the tank-car failed and if a rapid jet release preceded a BLEVE.

Ten video cameras, five still cameras and one high-speed camera are proposed. They will be positioned as shown in Figure 43. The cameras at the 500 m radius will be able to capture the behaviour of the pool fire and the entire effect of a tank-car failure. This could be useful in assessing fireball size and projectile trajectories. The cameras at the 200 m radius will obtain more detailed pictures of the pool fire behaviour and tank-car failure. The camera at the 50 m radius is controlled and viewed on a remote computer. It can be panned and tilted to view any occurrence of interest. It also acquires audio, which could help in identifying boil over and PRV opening. The high-speed camera is located at the 200 m radius so that the tank-car can fill its field of view. The effectiveness of the high-speed camera will depend on the obscuring effect of the pool fire. It is possible the fire will be thick enough to hide the entire tank-car.

8.1. Camera Protection

The cameras placed at the control bunker require no protection. If space and a clear view are available from inside the bunker they can be placed there. If not they can be located outside with no protection. The blast wave and thermal radiation will be sufficiently diminished to not adversely affect the cameras. It is possible a projectile could make it to the control bunker, but the chances are remote and the effort to provide additional protection, for the relatively inexpensive cameras, is not warranted.

The cameras at the 500 m radius could receive damage if the tank-car fails at a high fill level and will be placed in a protective shelter. The shelter will consist of a 2 m x 2 m x 2 m, 0.6 cm (¼ inch) thick steel plate box, with a door in the back and small openings in the front for the cameras to view the test. At this distance the openings are not required to be closed, maximizing the clarity of the view.

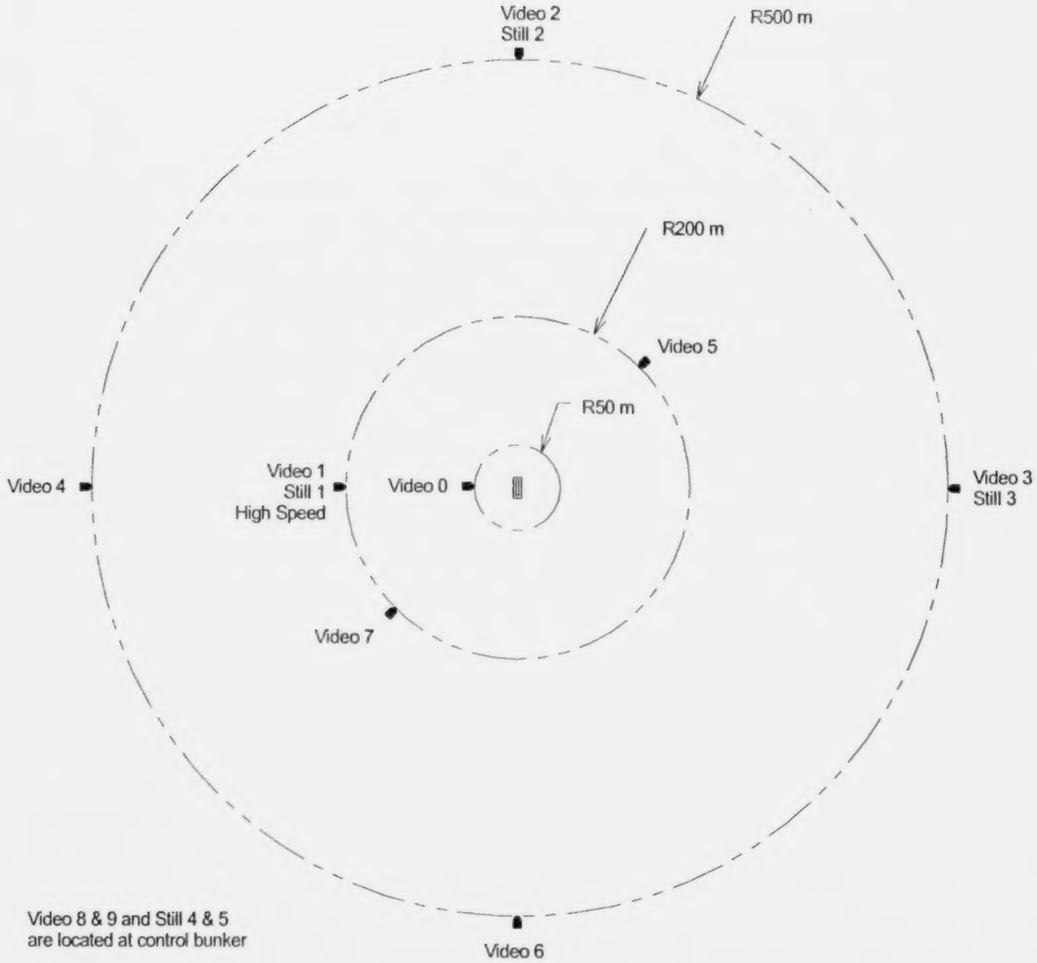

Video 2
Still 2
R500 m
R200 m
Video 5
R50 m
Video 4
Video 1
Still 1
High Speed
Video 0
Video 3
Still 3
Video 7
Video 8 & 9 and Still 4 & 5
are located at control bunker
Video 6

Figure 43: Video, still and high-speed camera locations

At the 200 m radius the same shelter will be used with the addition of a 1 m lip from the back, to prevent tipping, and plastic shields over the openings for the cameras. Due to the expense of the high-speed camera an earth embankment will be added to the front of the shelter to approximately 1 m high. The embankment will further ensure the shelter does not tip and reduce vibration as the high-speed camera is recording the blast effects.

The shelters at the 200 m radius also provide thermal protection from the fireball. The steel roof will act as an adequate radiation shield and heat sink to maintain a reasonable temperature within the shelter. Assuming that the front and top of the shelter receive the same thermal energy from the failure of a full tank-car as the ground, and that none of the energy is emitted, the shelter walls would increase by only 30°C. No further insulation is required to protect the cameras from thermal radiation, even under this extreme condition. Table 25 summarises the camera shelters required. If the testing is done at an explosives test site shelters may be available for rent, or included in the facility costs.

The camera at the 50 m radius will be lost in the case of a tank-car failure, since it will be engulfed in the fireball. It requires shielding to protect it from thermal radiation, from the pool fire, and a fan to provide cooling. A 0.15 m x 0.15 m x 0.15 m inside dimension box covered in a layer of insulation and another metal shell on the outside will suffice. The material will be 20 gauge steel. The front will be closed as much as possible while still allowing the desired field of view during camera panning and tilting. A small fan will be mounted at the back pushing air to the front. The camera and shield will be raised at least 1 m above the ground.

Table 25: Camera shelter summary

Location	Dimensions	Quantity
500 m (2,3,4,6)	2 m x 2 m x 2 m	4
200 m (1,5,7)	2 m x 2 m x 2 m + 1 m ext.	3
50 m (0)	0.17 m x 0.17 m x 0.17 m	1

8.2. Video Cameras

Digital video cameras are proposed for the ease of editing and sharing the data. Typical digital video cameras record to tapes of 1 hour duration. Since the test, including time for the pool fire to burn out, will last 2 hours this is insufficient. A 2 hour record time would allow for the entire test to be captured, but would not provide any buffer. In addition, it would require a control system and wiring to remotely activate the cameras, since they would have to start recording at the beginning of the test, when all personnel must be in the bunkers, to entirely record it.

To record longer times the camera could be connected to a computer and the video recorded directly to its hard drive, or special external hard drives purchased that connect to the digital output of the camera. Both of these options are expensive, the external hard drive is $900, and both add complexity to the system. The third option is to purchase cameras with built in hard drives. The lowest cost hard drive camera is less than $900, the same price as the special hard drive alone. The recommended camera is a Sony for $1,200. It includes a 30 GB hard drive and can record for up to 7.3 hours at high quality. The supplied battery only lasts for 1 hour. Although a battery that lasts for 4 hours can be purchased, a better option is to connect the camera to a portable power pack. It is half the price of the 4 hour camera battery, but will power the camera beyond the 7 hour recording capacity. Camera shelter 1 houses the high-speed camera and a wireless bridge for the computer network, in addition to the video and still cameras. A larger capacity power pack will be installed in this shelter to power all the electronics.

Hard drive storage will be required to store the video after the test. If the average test length, including start up and shutdown is 3 hours, 110 GB of storage is required per test. Two 250 GB portable hard drives would be sufficient for all 4 tests. The video will also be backed up on DVD or other media. The video system components are summarised in Table 26.

Video camera 0 is a web camera, connected to a computer in the control bunker via the network. This allows for remote viewing and control, as well as direct recording of the images on the computer. It has resolution below standard television image, only 320 x 240 pixels at 30 frames per second and no optical zoom. The low price of this camera is fitting to the location, which will receive thermal radiation from the pool fire and be destroyed if a tank-car fails, but a more expensive version (DCS-6620) is available. It has increased resolution and 10x optical zoom. This could be useful for examining the tank-car or other test apparatus in detail. This camera is located directly above the instrument bunker, which will supply the power. The image will be transmitted to the network hub in the bunker via a standard Ethernet cable.

The web camera will provide personnel in the control and visitor bunkers with real time images of the test. This could be very useful, since the bunkers are 1 and 2 km away from the tank-car. Command of the camera will be maintained in the control bunker. The panning ability will allow it to monitor the pool fire, but also observe other test equipment if a problem is suspected or verification of an action, such as valve opening, is required.

Table 26: Video camera component summary

Item	Model	Quantity
Video Camera	Sony DCRSR100	9
Power pack	Motomaster Eliminator 300A	7
Hard drive	250GB External	2
Web Camera	D-link DCS-5300	1

8.3. Still Pictures

In previous testing good results have been obtained from film cameras loaded with diapositive (slide) film. The resolution of this film is excellent, allowing poster sized prints to be made. For the same quality pictures film cameras are less expensive than digital. If digital images are required the slides can easily be scanned. For these reasons it is proposed to use film cameras instead of digital for the still pictures.

A good quality SLR camera is required that has a continuous shooting mode, manual exposure and focusing, and remote control connection. The Canon EOS Elan meets these requirements. Cable is also required to run from the instrument bunker to each camera to trigger them. Lenses are at least as important as the camera body. Good quality zoom lenses were chosen to provide flexibility in the field of view. For the cameras in position 1, 2, 3 and 4 a 28-105 mm lens provides a good field of view. For position 5, at the control bunker, a 100-300 mm lens allows for additional zooming in on the tank-car. Figure 44 shows the fields of view obtained with the extreme settings from 200 m, 500 m and 1000 m from the tank-car. Table 27 summarises the required cameras, lenses and cables. The camera bodies could be replaced with digital versions, but the costs would significantly increase.

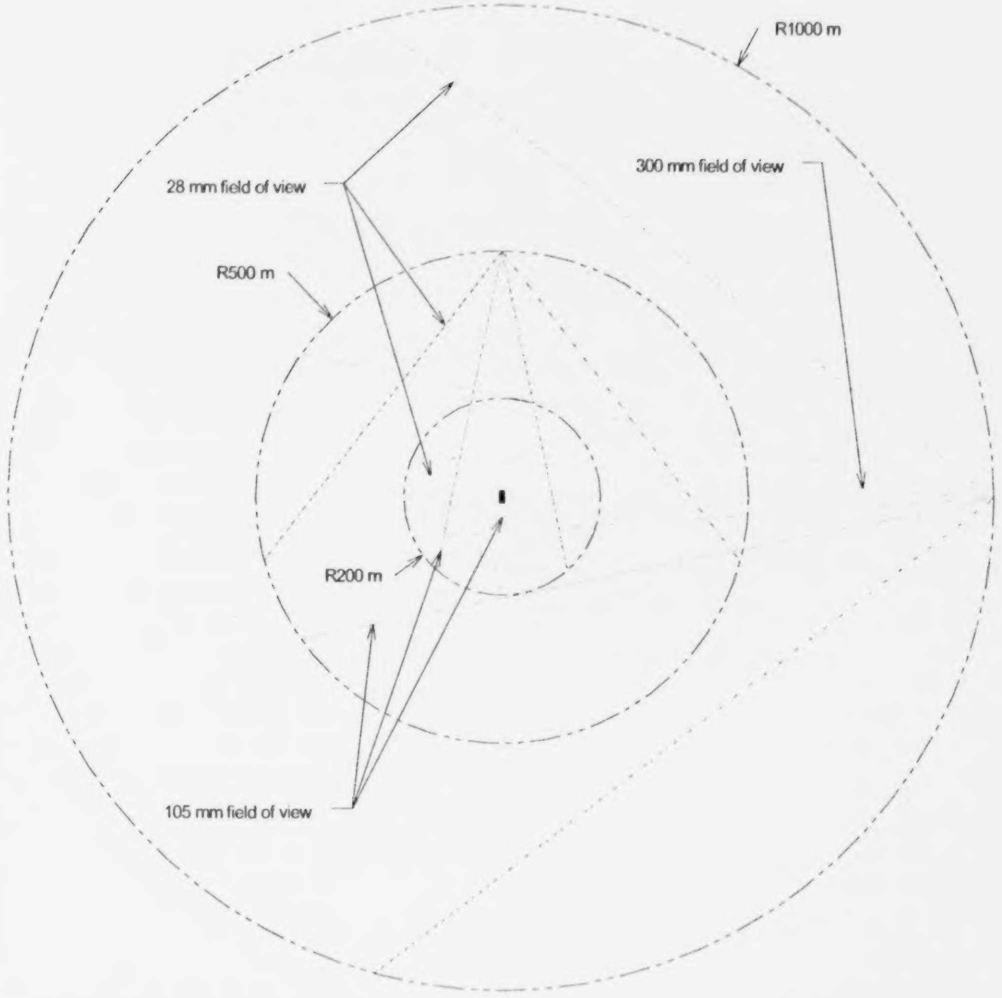

R1000 m
28 mm field of view
300 mm field of view
R500 m
R200 m
105 mm field of view

Figure 44: Field of view for still cameras at 200 m, 500 m and 1000 m from tank-car with 28 mm, 105 mm and 300 mm lenses

Table 27: Still camera component summary

Item	Model	Quantity
SLR Camera	Canon ELAN 7N	5
Zoom lens	Canon EF 28-105 mm/3.5-4.5USM	4
Zoom lens	Canon EF 100-300 mm/4.5-5.6USM	1
Remote cable	2 conductor, shielded, 22ga	1

8.4. High-Speed Camera

A high-speed camera capable of recording for approximately 10 seconds at 300 frames per second is required. It will be triggered manually from the control bunker, if the tank-car fails. Two seconds of record time are pre-trigger to allow for the reaction time of the operator. The remaining 8 seconds are post trigger.

The Phantom V4.2 camera meets the requirements and is available for rent. A summary of the components for the high-speed camera is given in Table 28. A computer or video recording device will also be required to download the data from the camera after the test. The digital video camera may be able to download the data to its hard drive for temporary storage. The video and high-speed power packs in this camera shelter should be combined in a larger pack, with more storage capacity, to supply both cameras and the wireless equipment located in this shelter.

Table 28: High-speed camera component summary

Item	Model	Quantity
Camera system	Phantom V4.2 (Rental)	1
Power pack	Motomaster Eliminator	1
Remote cable	2 conductor, shielded, 22ga	1

9. Data Acquisition and Control

This section describes the data acquisition systems required for the testing. The systems will be PC based. The primary computers and data acquisition system will be located in the instrument bunker, buried 50 m from the tank location. These computers will be linked by wireless communication to computers in the control bunker 1000 m from the tank. The computers at the control bunker will interface with the close in computers by remote access software, such as Symantec pcAnywhere.

9.1. Low-Speed Data Acquisition and Control

9.1.1. Hardware

The low-speed data acquisition and control system records the majority of the test data and performs the computer initiated control functions. The low-speed data acquisition and control requirements are summarised in Table 29. The large scale of this test results in a high channel count system. 507 analog inputs, of which 490 are thermocouples, and 10 digital outputs are required to measure and control the test.

Table 29: Low-speed data acquisition input and output requirements

Instrument/Device	Analog Inputs	Digital Outputs	Freq. (Hz)	Range
Lading TCs	228		1	25 mV (600°C)
Wall TCs	143		1	50 mV (1230°C)
Jacket and PRV TCs	47		1	50 mV (1230°C)
Fire TCs	31		1	55 mV (1370°C)
Calorimeter TCs	33		1	±5 mv (-150 to 120°C)
Radiometer	1		100	50 mV
Radiometers via transmitter	5		100	1-5V (5-20 mA)
Fire Pan Thermocouples	7		1	50 mV (1230°C)
Calorimeter Flowmeter	3		1	1 to 5V (5-20 mA)
Pressure Transducers	4		10	1-5V (5-20 mA)
Level Transducer	1		1	1 to 5V (5-20 mA)
Wind Transducers	4		0.1	1 to 5V (5-20 mA)
Fuel Pump		1	1	1/0
Fuel Valve		1	1	1/0
Water Pump		1	1	1/0
Water Valve		1	1	1/0
Vapour Vent Line		1	1	1/0
Spark Igniters		1	1	1/0
Ignition burner valve		1	1	1/0
Calorimeter pumps		3	1	1/0
Total	**507 (490 TCs)**	**10**	▨	▨

A National Instruments system was chosen for the low-speed data acquisition and control. It comes complete with terminal blocks, DAC boards and computer in a rugged industrial housing designed to operate in temperatures up to 55°C. Purchasing a complete package provides assurance that all the components will work together with a minimum of conflicts. The industrial design makes it ideal for field work were it can be subjected to temperature variations, vibration and shock. The price of the National Instruments system was comparable to other data acquisition systems pieced together separately, without the additional ruggedness.

To achieve the 490 thermocouple input channels two complete systems are required. Both systems have eight DAC boards, each with 32 analog inputs suitable for thermocouples, but 1 channel on each board is required for cold junction compensation leaving a total of 496 channels. The additional analog inputs and digital outputs are provided by an extra board on one of the systems that adds 16 analog inputs and the required digital control channels.

The advantage of two complete DA systems is redundancy. If one fails the other will continue to function, and half of the data will be preserved and continue to be recorded. Unless the system failure is caused by an external event, the chance of both systems failing simultaneously is very low. The inputs to each system will be divided so that a failure will reduce the spatial resolution of the thermocouples, but still provide a sampling across the geometry of the tank-car. For example the centre array, centre profile probe would assign the thermocouples at the 10%, 30%, 50%, 70%, 85%, 95% and 100% fill levels to system 1 and at the 20%, 40%, 60%, 80%, 90% and 99% to system 2. A general division of the inputs and outputs between the two systems is suggested in Table 30.

All the control inputs are located in system 2, because it contains all the outputs. If system 2 failed the calorimeter would shut down and the fuel supply would not operate. Depending on the time in the test enough fuel may remain in the pan to complete the test, or manual control may be possible using the web camera and fuel burn-off rates.

9.1.2. Software

LabView software was chosen to program the data acquisition system. LabView is a National Instruments product, which reduces the chances of conflict between the hardware and software, since the hardware is also produced by National Instruments. LabView is a programming system that allows the programmer to acquire voltages from the DAC board, convert them to engineering units, save the data to files, display the data, either graphically or numerically, and make and execute control decisions.

Table 30: Division of inputs and outputs between DAC systems

Channel Type	Instrument/Device	System 1 Channels	System 2 Channels
Analog Inputs	Lading Thermocouples	114	114
	Wall Thermocouples	71	72
	Jacket and PRV Thermocouples	23	24
	Fire Thermocouples	15	16
	Calorimeter Thermocouples	16	17
	Radiometers	3	3
	Fire Pan Fuel Control Thermocouples	0	7
	Level Transducer	0	1
	Conductivity Meter	0	1
	Pressure Transducers	2	2
	Wind Transducers	2	2
	Calorimeter Flow Meters	1	2
	Total Required	**247**	**261**
	Available	***248***	***264***
Digital Outputs	Fuel Pump	0	1
	Fuel Valve	0	1
	Water Pump	0	1
	Water Valve	0	1
	Vapour vent line	0	1
	Spark Igniters	0	1
	Ignition burner valve	0	1
	Calorimeter pumps	0	3
	Total Required	**0**	**10**
	Available	***0***	***24***

Two LabView programs will have to be written. The first, for system 1, will acquire data, convert it to engineering units, display results as the test progresses, save the data to the hard drive and notify the user when temperature and pressure limits are exceeded in the tank-car. The second program will be a replica of the first, with the addition of the controls for the calorimeters, fuel flow, water flow, vapour vent, ignition system and calculation of time until failure. Communication through the network will be required between the two systems for time to failure analysis, and reporting average and maximum temperatures.

A preliminary user interface for the data acquisition and control computer, sized for a 1280x1024 resolution screen, is given in Figure 45 and Figure 46. This display assumes that the maximum, minimum and average temperatures, and all pressure readings are transmitted from the data acquisition only system to allow an accurate summary to be produced on this display. Figure 45 shows the first page, which includes the test controls in the top row. The controls activate all the computer controlled systems, and determine whether the fuel and water supply are directly operated by the user or automatically activated by the computer. The event marker is used to indicate when something noteworthy occurs. It can increment automatically, such as when the pool fire ignition is activated, or when the user clicks on the button, for example to mark a change in wind direction or the activation of still cameras.

The second row controls the fuel and water supply system. It allows the user to decide which of the pool level sensors to use for control, and displays all the results from those sensors. It also has an area to display any warnings the computer generates related to the level sensors, fuel overflow, conflicts between sensors etc.

The third row summarises the test. In addition to temperatures and tank pressure, it provides an estimated time until failure and the current accumulated damage for the tank. A box is provided for warnings and errors generated by the system. These include DAC system status, pool fire status, calorimeter flow problems and whether the tank is expected to survive the test. Any detected problem will appear in this box.

The next page, shown in Figure 47, provides more detailed results. Although shown as pages, the display is continuous and the user scrolls down through it. When the detailed results are shown the page is set up so that the test summary is still visible. This means that the crucial information is visible whichever section of the display is being viewed.

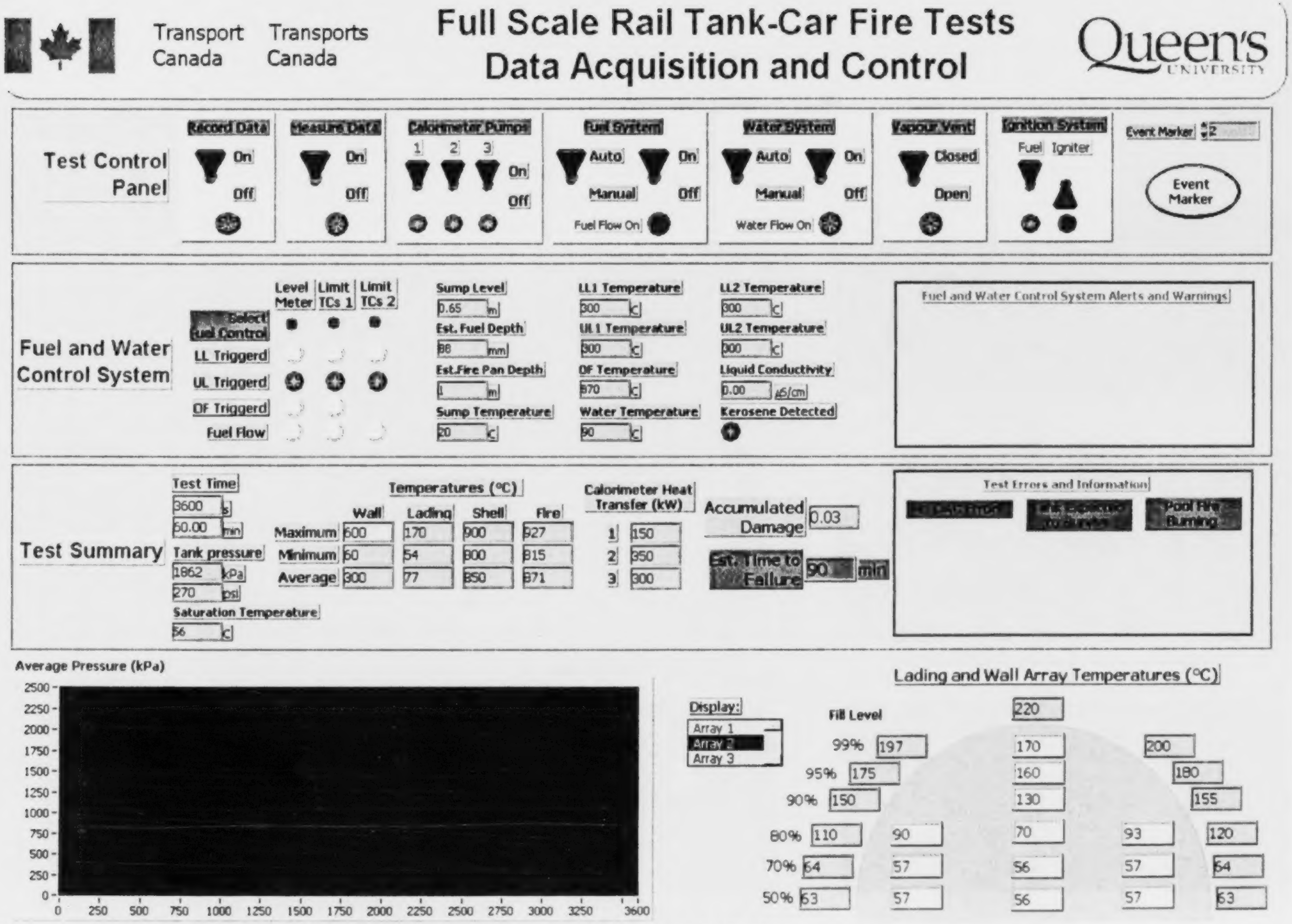
The detailed display provides plots of tank pressure, lading, wall, and fire temperatures. It also displays a selection of wall and lading thermocouples, from the arrays installed on the tank-car. Only one array is shown at a time but it can be switched to the others with the selection box.

The objectives of the display are to provide information to allow informed decisions about the test operation. It must also allow easy control of the test. In an emergency the control switches must be easily identified and activated. Colour is used to highlight critical information. For example red is used to indicate important results or controls, and bright yellow for information often of interest. This allows those items to stand out. The object of the display is not to show all the test data. The majority of the data will be analysed post test.

Additional controls, not shown, appear below the detailed display. These include items such as:

- File prefix – to identify data files associated with particular test
- Calibration constants for sensors
- Ranges for thermocouples
- Selection of thermocouples to plot
- Data acquisition system settings

Additional displays could be set up on other computers to show details of thermal defect temperatures, temperature distribution in the fire and other items of interest, but not required for primary test control.


Transport Canada
Transports Canada
Full Scale Rail Tank-Car Fire Tests
Data Acquisition and Control
Queen's UNIVERSITY
Test Control Panel
Record Data
On
Off
Measure Data
On
Off
Calorimeter Pumps
1
2
3
On
Off
Fuel System
Auto
Manual
On
Off
Fuel Flow On
Water System
Auto
Manual
On
Off
Water Flow On
Vapour Vent
Closed
Open
Ignition System
Fuel
Igniter
Event Marker
Event Marker
Fuel and Water Control System
Level Meter
Limit TCs 1
Limit TCs 2
Select Fuel Control
LL Triggerd
UL Triggerd
OF Triggerd
Fuel Flow
Fuel and Water Control System Alerts and Warnings
Test Summary
Test Errors and Information
Pool Fire Burning
Average Pressure (kPa)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3600
Lading and Wall Array Temperatures (°C)
Display:
Array 1
Array 2
Array 3
Fill Level

Event Marker 2

Sump Level 0.65 m
Est. Fuel Depth 88 mm
Est.Fire Pan Depth 1 m
Sump Temperature 20 C
LL1 Temperature 300 C
UL1 Temperature 300 C
OF Temperature 870 C
Water Temperature 90 C
LL2 Temperature 300 C
UL2 Temperature 300 C
Liquid Conductivity 0.00 µS/cm
Kerosene Detected

Test Time 3600 s
60.00 min
Tank pressure 1862 kPa
270 psi
Saturation Temperature 56 C

Temperatures (°C)

	Wall	Lading	Shell	Fire
Maximum	600	170	900	927
Minimum	60	54	800	815
Average	300	77	850	871

Calorimeter Heat Transfer (kW)

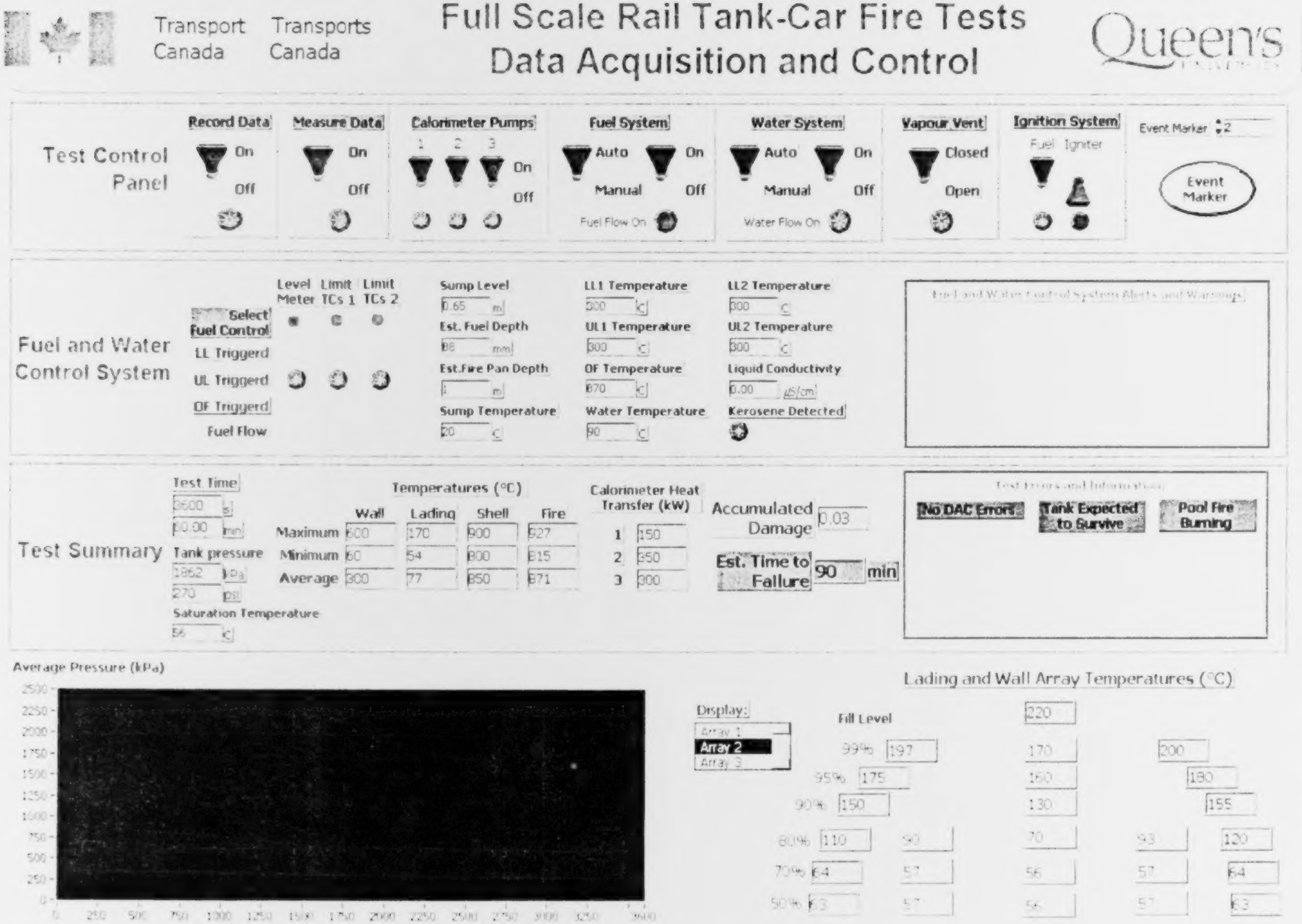
1	150
2	350
3	300

Accumulated Damage 0.03
Est. Time to Failure 90 min

Display: Array 2

Fill Level					
			220		
99%	197		170	200	
95%	175		160	180	
90%	150		130	155	
80%	110	90	70	93	120
70%	64	57	56	57	64
50%	63	57	56	57	63

Figure 45: Top page of low-speed data acquisition and control display


Transport Canada
Transports Canada
Queen's University
Record Data
Measure Data
Calorimeter Pumps
1
2
3
Fuel System
Water System
Vapour Vent
Ignition System
Fuel
Igniter
On
Off
Auto
Manual
Closed
Open
Fuel Flow On
Water Flow On
Event Marker
Test Control Panel
Fuel and Water Control System
Select Fuel Control
Level Meter
Limit TCs 1
Limit TCs 2
LL Triggerd
UL Triggerd
OF Triggerd
Fuel Flow
Kerosene Detected
Fuel and Water Control System Alerts and Warnings
Test Summary
Test Errors and Information
No DAC Errors
Tank Expected to Survive
Pool Fire Burning
Average Pressure (kPa)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3600
Display:
Array 1
Array 2
Array 3

Full Scale Rail Tank-Car Fire Tests
Data Acquisition and Control

Event Marker 2

Sump Level 0.65 m
Est. Fuel Depth 88 mm
Est.Fire Pan Depth 1 m
Sump Temperature 20 C
LL1 Temperature 300 C
UL1 Temperature 300 C
OF Temperature 870 C
Water Temperature 90 C
LL2 Temperature 300 C
UL2 Temperature 300 C
Liquid Conductivity 0.00 µS/cm

Test Time 3600 s
60.00 min
Tank pressure 1862 kPa
270 psi
Saturation Temperature 56 C

Temperatures (°C)	Wall	Lading	Shell	Fire
Maximum	600	170	900	927
Minimum	60	54	800	815
Average	300	77	850	871

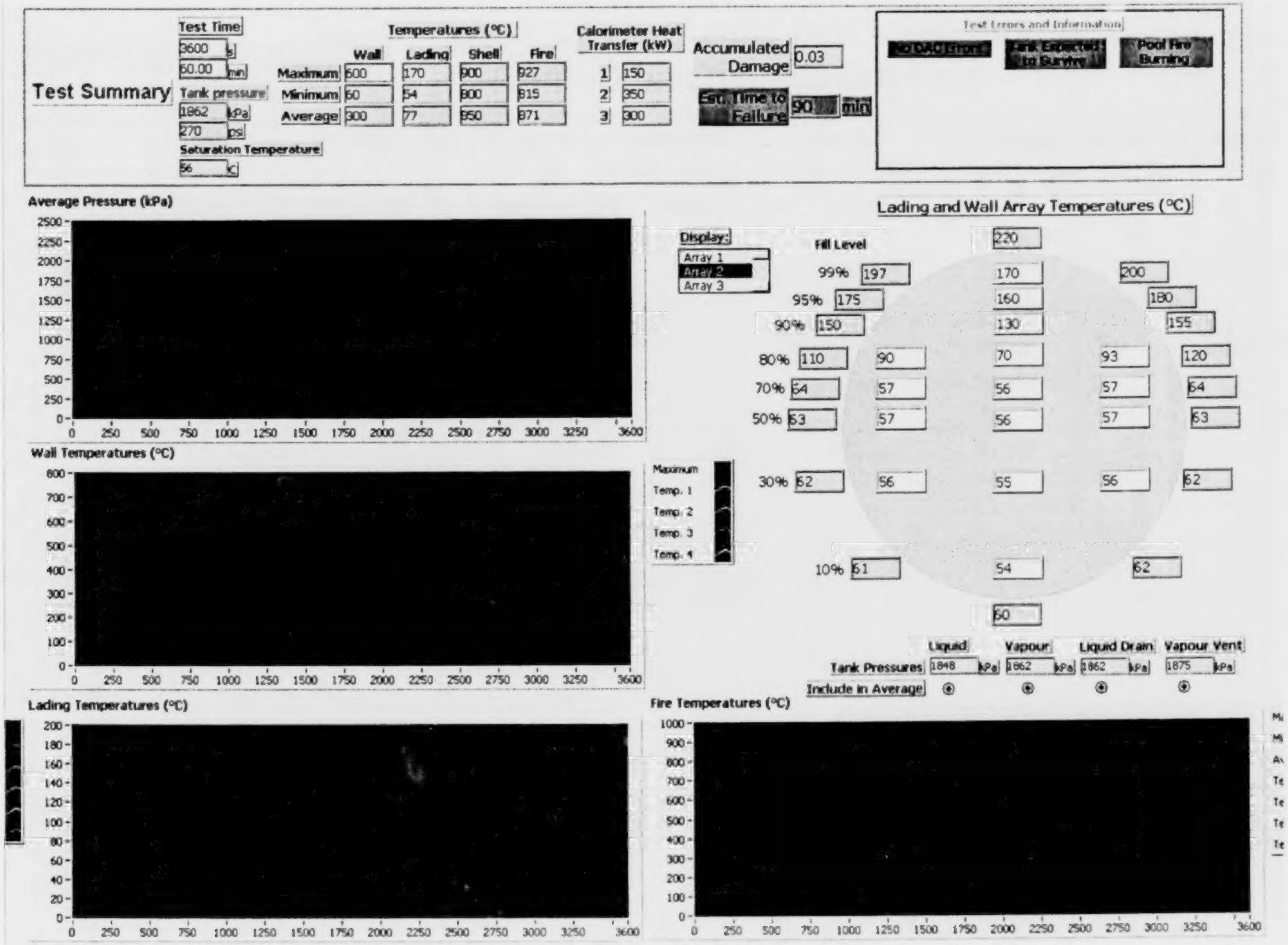
Calorimeter Heat Transfer (kW)	
1	150
2	350
3	300

Accumulated Damage 0.03
Est. Time to Failure 90 min

Lading and Wall Array Temperatures (°C)

Fill Level					
			220		
99%	197		170		200
95%	175		160		180
90%	150		130		155
80%	110	90	70	93	120
70%	64	57	56	57	64
50%	63	57	56	57	63

Figure 45: Top page of low-speed data acquisition and control display


Test Errors and Information
No DAQ Errors
Tank Expected to Survive
Pool Fire Burning
Display:
Array 1
Array 2
Array 3
Average Pressure (kPa)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3600
Wall Temperatures (°C)
800
700
600
500
400
300
200
100
0
0 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3600
Maximum
Temp. 1
Temp. 2
Temp. 3
Temp. 4
Lading Temperatures (°C)
200
180
160
140
120
100
80
60
40
20
0
0 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3600
Fire Temperatures (°C)
1000
900
800
700
600
500
400
300
200
100
0
0 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3600

Test Summary

Test Time
3600 s
60.00 min

Tank pressure
1862 kPa
270 psi

Saturation Temperature
56 C

	Temperatures (°C)			
	Wall	Lading	Shell	Fire
Maximum	600	170	900	927
Minimum	60	54	800	815
Average	300	77	850	871

Calorimeter Heat Transfer (kW)	
1	150
2	350
3	300

Accumulated Damage 0.03

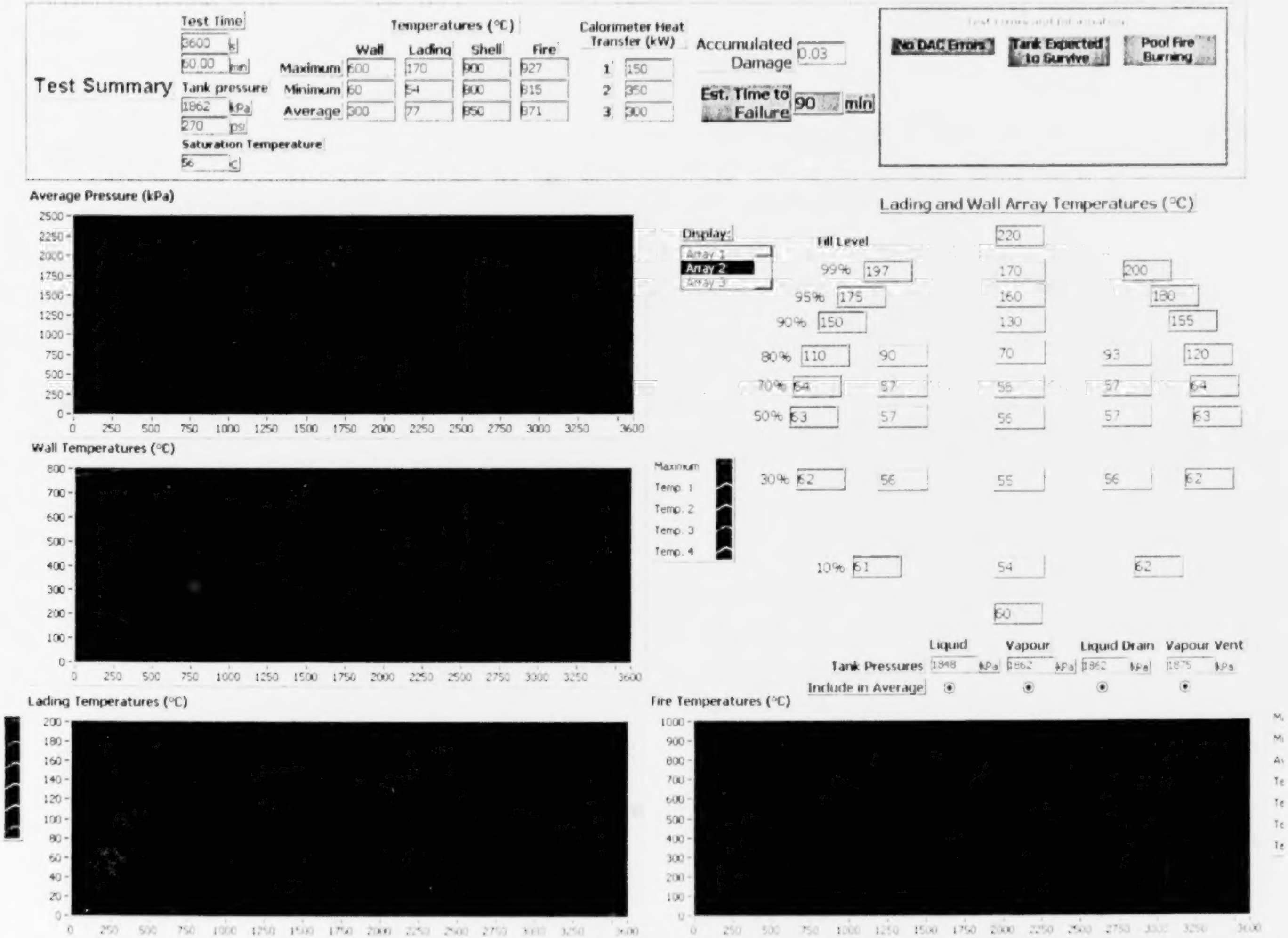
Est. Time to Failure 90 min

Lading and Wall Array Temperatures (°C)

Fill Level					
			220		
99%	197		170		200
95%	175		160		180
90%	150		130		155
80%	110	90	70	93	120
70%	64	57	56	57	64
50%	63	57	56	57	63
30%	62	56	55	56	62
10%	61		54		62
			60		

	Liquid	Vapour	Liquid Drain	Vapour Vent
Tank Pressures	1848 kPa	1862 kPa	1862 kPa	1875 kPa
Include in Average	●	●	●	●

Figure 46: Second page of low-speed data acquisition and control display



Test Summary

Test Time
3600 s
60.00 min

Tank pressure
1862 kPa
270 psi

Saturation Temperature
56 C

	Wall	Lading	Shell	Fire
Maximum	600	170	900	927
Minimum	60	54	800	815
Average	300	77	850	871

Calorimeter Heat Transfer (kW)	
1	150
2	350
3	300

Accumulated Damage 0.03

Est. Time to Failure 90 min

No DAC Errors

Tank Expected to Survive

Pool Fire Burning

Lading and Wall Array Temperatures (°C)

Display: Array 2

Fill Level					
			220		
99%	197		170		200
95%	175		160		180
90%	150		130		155
80%	110	90	70	93	120
70%	64	57	56	57	64
50%	63	57	56	57	63
30%	62	56	55	56	62
10%	61		54		62
			60		

	Liquid	Vapour	Liquid Drain	Vapour Vent
Tank Pressures	1848 kPa	1862 kPa	1862 kPa	1875 kPa
Include in Average	●	●	●	●

Average Pressure (kPa)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3600
Array 1
Array 2
Array 3
Wall Temperatures (°C)
800
700
600
500
400
300
200
100
0
Maximum
Temp. 1
Temp. 2
Temp. 3
Temp. 4
Lading Temperatures (°C)
200
180
160
140
120
100
80
60
40
20
0
Fire Temperatures (°C)
1000
900
800
700
600
500
400
300
200
100
0

Figure 46: Second page of low-speed data acquisition and control display

9.2. High-Speed Data Acquisition

9.2.1. Hardware

The high-speed data acquisition system requires only 14 channels. A Data Translation DAC board, in standard desktop PC, was chosen for this task. The required components are summarised in Table 31. The DT3010/32-268 board has a maximum throughput of 1250 kSamples/s over 16 channels. Using only 14 channels results in an acquisition rate of 89 kHz per channel. The addition of extra boards would increase the available rate by decreasing the number of channels per board.

Table 31: High-speed data acquisition components

Component	Part	Quantity
DAC Board	DT3010/32-268	1
Terminal Board	DT740	1
Cable	EP307	1
Computer	PC	1

9.2.2. Software

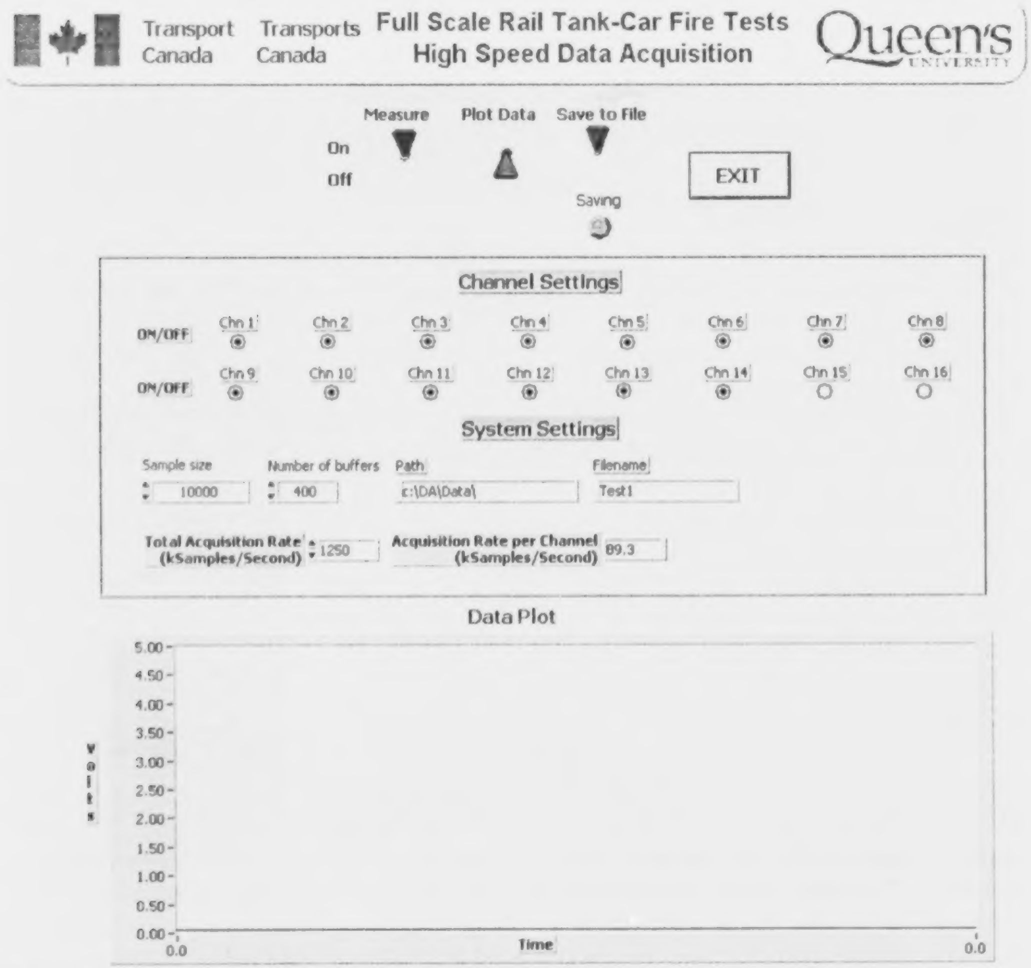
For consistency LabView is recommended to acquire the high-speed data. Due to the high data throughput the program will be kept as simple as possible. All processing and data display will occur once the test has concluded. Plotting the data in real time serves no purpose as the results occur too quickly. Data plotting is required in the program for testing and debugging, but will not be used during the test. Figure 47 is a sample front end for the high-speed data acquisition system using LabView. It includes the following components to control how the data is acquired and presented:

1. Turn each channel ON/OFF
2. Acquisition rate
3. Path and filename for data to be written to
4. Measure data ON/OFF
5. Record data ON/OFF
6. Plot data ON/OFF
7. Exit the program

A sample high-speed data file follows. This sample shows only 5 blast gauges and the high-speed pressure gauge. The actual file will have additional columns for blast gauges and the standard pressure transducer. The date and time the file is created are included as a reference. The header line appears once then the data follows. The period, as provided by the data acquisition board, is in the first column. A post processing summation of this value will provide the time from the start of the file. A 100 minute test at 89 kHz will have approximately 540 million lines of data in the file. The final line is a series of -1 values to indicate to the post processing programs that the end of file is reached. The operating system and hard drive in the computer used for high-speed data acquisition must be able to handle files of this size and continuous writing to the disk. The size of the file could be reduced by triggering the high-speed acquisition just prior to the first opening of the relief valve, based on tank-car pressure.

Sample of high-speed file:

```
Date:   2006-04-17
Time:   16:15:20
Period (ms)   BG1 (V)   BG2 (V)   BG3 (V)   BG4 (V)   BG5 (V)   HSP (V)
0.011236      0.123     1.234     2.345     3.456     4.567     5.678
0.011236      1.234     2.345     3.456     4.567     5.678     0.123
0.011235      2.345     3.456     4.567     5.678     0.123     1.234
-1            -1        -1        -1        -1        -1        -1
```


Transport Canada
Transports Canada
Full Scale Rail Tank-Car Fire Tests
High Speed Data Acquisition
Queen's University
Measure
Plot Data
Save to File
On
Off
Saving
EXIT
Data Plot
Volts
Time
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.0
0.0

Channel Settings

ON/OFF Chn 1 ● Chn 2 ● Chn 3 ● Chn 4 ● Chn 5 ● Chn 6 ● Chn 7 ● Chn 8 ●

ON/OFF Chn 9 ● Chn 10 ● Chn 11 ● Chn 12 ● Chn 13 ● Chn 14 ● Chn 15 ○ Chn 16 ○

System Settings

Sample size: 10000
Number of buffers: 400
Path: c:\DA\Data\
Filename: Test1
Total Acquisition Rate (kSamples/Second): 1250
Acquisition Rate per Channel (kSamples/Second): 89.3

Figure 47: High-speed data acquisition display

10. Computer and Control Network

The computer network links all the computers and the webcam, allowing remote control and viewing of the test from the control bunker. All the instrument bunker computers will be remotely controlled from the control bunker, and some will be monitored from the visitor bunker.

The control network transmits the control voltage from the manual switches in the control bunker, and provides a backup link to read a pressure transducer.

10.1. Computer Network

Since the instrument, control and visitor bunkers are up to one kilometre apart, fibre optic cables or wireless networks, are required to connect them. A hub is required in each bunker to allow the devices to connect to the network.

10.1.1. Fibre Optic Network

The advantage of fibre optic cables is the immunity to electromagnetic interference, but the disadvantages are cost and susceptibility to mechanical breakage due to animal or human damage. Since the control and fibre optic cables would follow the same path, the chances of both failing simultaneously are increased.

Fibre optic cables would be connected to the network in each bunker through a media converter. The instrument and visitor bunkers require one converter each, while the control bunker requires two converters to connect to both the control and visitor bunker. The fibre optic network layout is shown in Figure 48. The required components are given in Table 32.

The fibre optic cable would have to be buried under at least 10 cm of soil out to a radius of 150 m from the tank-car. The cable would be covered with a few centimetres out to a 400 m radius. Out to 600 m it would be covered. This provides protection from the thermal load due to the pool fire, and, if the tank-car fails, the fireball.

Table 32: Fibre optic computer network component specifications

Component	Quantity
Multi-mode, duplex, fibre optic cable 1200 m long	2
Media converter - TRT CXL-32 m1-2	4
8 Port Network Hub	3
100 ft. Cat. 5e Ethernet cable (for web camera)	1
25 ft. Cat. 5e Ethernet cable	10
3 ft. Cat. 5e Ethernet cable	5

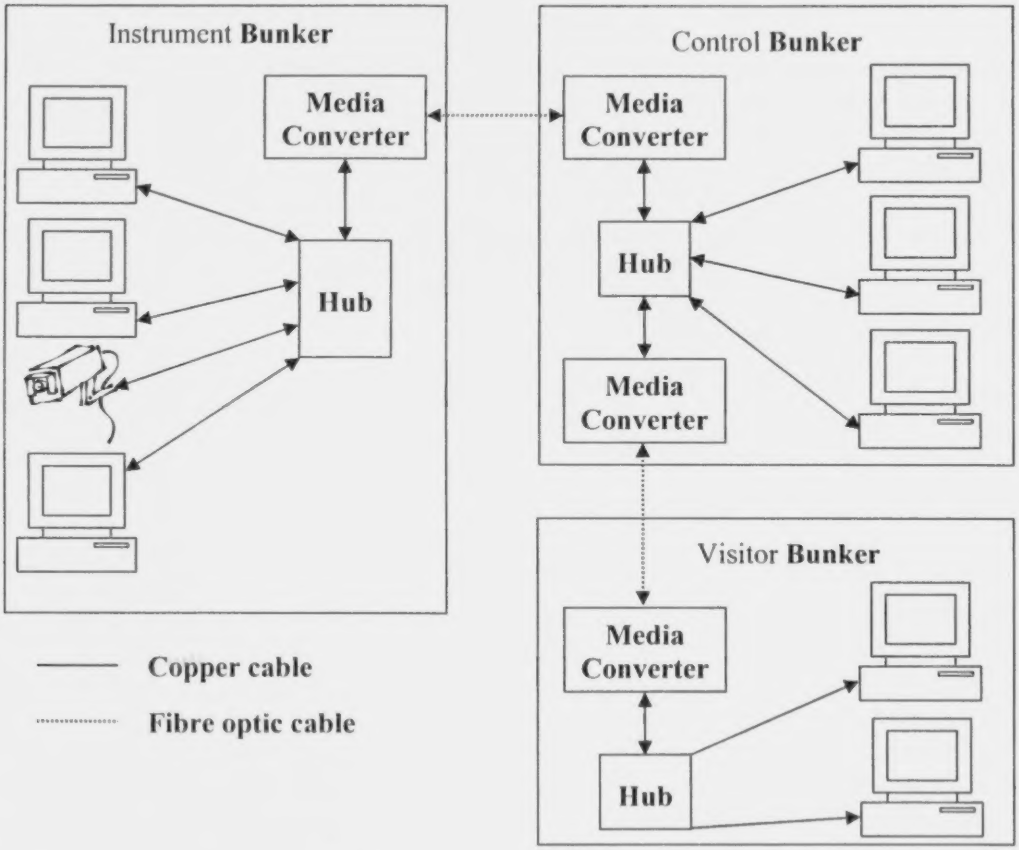

Instrument Bunker
Media Converter
Hub
Control Bunker
Media Converter
Hub
Media Converter
Visitor Bunker
Media Converter
Hub
Copper cable
Fibre optic cable

Figure 48: Fibre optic computer network schematic

10.1.2. Wireless Network

Due to the lower cost and separation from the control network a wireless system is preferred. The wireless network requires high power, range boosting antennas. A network cable will connect the instrument bunker to a wireless bridge with antenna, at camera shelter 1, which is 150 m behind the instrument bunker. This will move the antenna beyond the fireball radius. The antenna will be mounted on the roof of the camera shelter with a steel shield to protect it from the blast wave and thermal radiation from the fireball. It will be a directional antenna aimed at the control bunker. A directional antenna will also be located in the visitor bunker, and a non-directional antenna will be connected at the control bunker. The network router will be located at the control bunker and bridges will be used in the camera shelter and visitor bunker. The wireless network layout is shown in Figure 49 and the components are given in Table 33.

The wireless system will be extensively verified at the site under all possible test conditions before being relied upon. During test set site preparation it will be checked under various weather conditions that could occur during the test. The testing is precautionary, since the range on the antennas is up to 8 km, but it is important to verify field operability. For redundancy a second broadcast point from the instrument bunker could be installed on a tower 50 m behind the instrument bunker. This may be destroyed in the case of a tank-car failure, but would provide a backup in other situations.

Table 33: Wireless computer network component specifications

Component	Quantity
Wireless router (D-Link DI-624)	1
Wireless Ethernet bridge (D-Link DWL-G-820)	2
14dBi Directional Antenna (TrendNet T56-2000)	2
9dBi Omni-directional antenna (Hawking H300-2080)	1
8 Port Network Hub	2
500 ft. Cat. 5e Ethernet cable (to camera shelter)	1
100 ft. Cat. 5e Ethernet cable (for web camera)	1
25 ft. Cat. 5e Ethernet cable	10
3 ft. Cat. 5e Ethernet cable	5

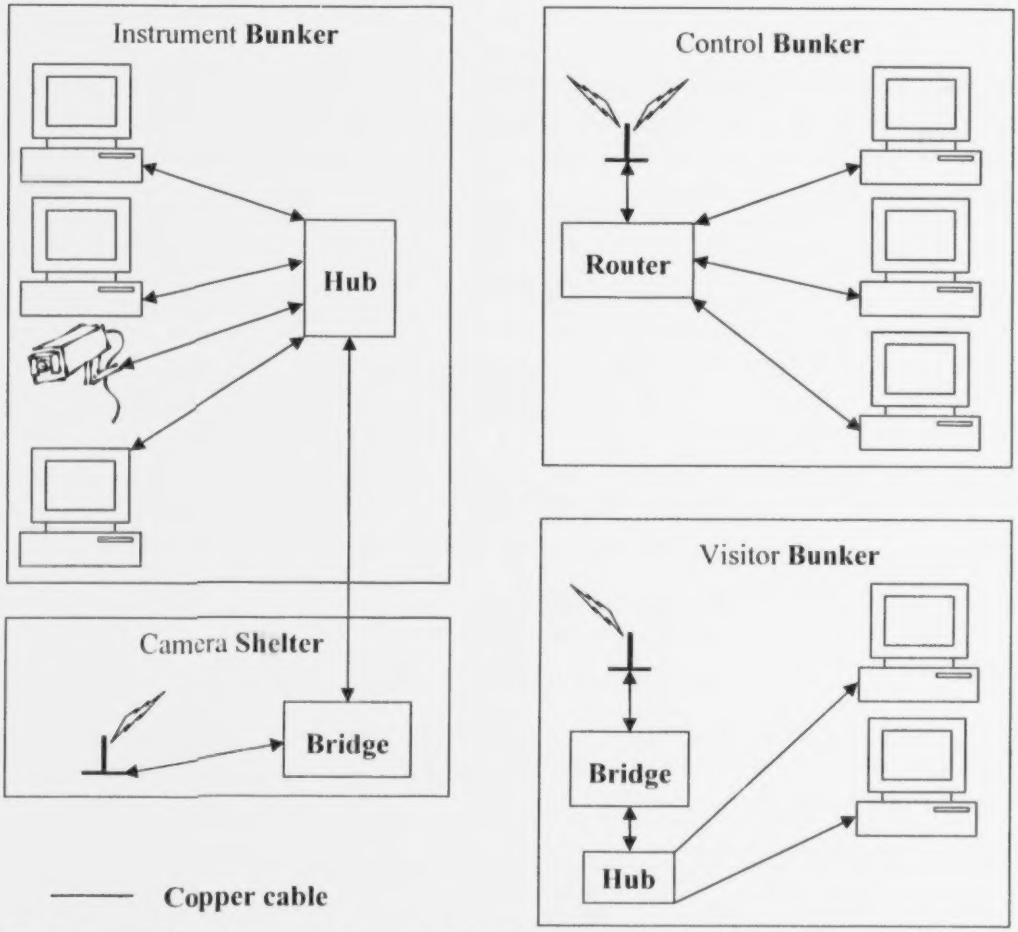

Instrument Bunker
Hub
Camera Shelter
Bridge
Control Bunker
Router
Visitor Bunker
Bridge
Hub
Copper cable

Figure 49: Wireless computer network schematic

10.2. Software

Each computer on the network that needs to be remotely controlled or control remotely will be running Symantec pcAnywhere. This software allows a remote computer to take control of, or view, a host. A computer in the control bunker will act as if it were the computer in the instrument bunker, displaying its video screen and sending the mouse and keyboard inputs back to it. It also allows the visitors to monitor the test. The computers being controlled are the hosts and do not require the full version of the software, reducing the cost of the system.

The following computers will require pcAnywhere:

DAC computer 1 – Host version only
DAC computer 2 – Host version only
High-speed DA computer – Host version only
Control bunker main computer – Full version
Control bunker secondary computer – Full version
Control bunker backup computer – Full version
Visitor bunker monitoring computer – Full version

The computers displaying the images from the webcam do not require pcAnywhere as they are viewed and controlled via their own software. Five licenses of the software are available for the price of four so the full version will be purchased in this format. Although it adds to the cost of the host version, it should also be purchased in this form to allow for flexibility in the setup.

10.3. Control Network

In addition to the computer network, a control system is required. This provides backup to the computer control system for the pool fire fuel controls and allows direct control of the tank-car vent valves and still cameras. The wiring diagram for the system is provided in the control strategy section of the report. The object of this section is to give the cabling requirements.

Between the instrument bunker and the control bunker the following conductors are required:

8 for manual control switches
1 for common to manual control switches
3 for backup pressure transducer measurement
12 total

To connect the instrument and control bunkers requires about a kilometre of cable. This should be verified once the test site location and layout is known. The required cable is summarised in Table 34.

Table 34: Control network cable specifications

Cable	Quantity
12 conductor, 22ga, shielded, 1000 foot long Belden P/N 8457-60-1000	3
12 conductor, 22ga, shielded, 500 foot long Belden P/N 8457-60-500	1

11. Control System

The control system is actuated by both manual inputs and the computer. The computer control has the advantage that it can make decisions independent of human input. This is ideal for actions depending on constant monitoring, or requiring calculations.

11.1. Control System Failure

Communication for the computer controlled components is through the computer network. The disadvantage of this system is that if the control computer crashes during the test then control is lost. If the main power goes down then control is lost to both the computer and manual control system.

If computer control is lost then the manual override system will be used. Each manual control requires a conductor from the instrument to the control bunker. As long as the conductors remain unbroken, and the power is on, the manual controls will function. If the control power supply fails control will be lost, but this affects the computer control as well as the manual.

If power is lost then there must be an alternate power supply that can quickly be started. This would probably take the form of a generator with automatic start wired into the main power supply.

The computers and data acquisition systems at the instrument bunker will be connected to an uninterruptible power supply (UPS). The normally open vapour vent, normally closed liquid drain valves and control relays will also be energized by the UPS. This means if power is lost the following will happen:

i) Data acquisition computers will continue to operate.
ii) Power supplies and signal conditioners will continue to operate.
iii) System will keep recording data.
iv) Vapour and liquid drain valves will remain closed and under control.
v) The fuel pump will stop and the fuel valve will close.
vi) The water supply pump will stop and water valve will close.
vii) Calorimeter pumps will stop.
viii) The test will not abort unless UPS fails or the operator commands it.

If power is restored within minutes then the following will take place

i) Fuel flow can be restarted.
ii) Water supply flow can be restarted.
iii) Calorimeter pumps restart.
iv) Test continues.

In the unlikely event of complete loss of control and data collection, the fuel pumps will shut down, the vapour valve will open and the test will abort. The following UPS system is recommended:

1 - APC Smart – UPS 3000VA 120V
1 - SU48BP battery unit

This system will provide 45 minutes of backup power. If the backup generator or main power cannot be restored this allows time for the fuel in the fire pan to burn-off and the tank to be monitored during the initial stages of depressurisation.

11.2. Electro-mechanical Control System

The electro-mechanical control system refers to the relays, switches, valves, motors etc. involved in the control system. It includes the computer controlled relays, but does not provide the logic behind their actuation. A manual override system is included. This system provides manual operation at the control bunker in the event computer control is lost. This manual system would be used to do the following:

i) Fuel pump on/off.
ii) Fuel valve open/close.
iii) Vapour vent valve open/close.
iv) Liquid drain line open/close.
v) Still camera activation.

Two possible control systems are presented in Appendix I. The first is designed to maximise safety by defaulting to the safest setting. The second is designed for maximum test robustness. It defaults to the condition most likely to allow the test to either continue, or be resumed at a later time. The proposed system, presented here, balances these often conflicting requirements.

The control system is designed to provide a safe test, but allow it to be salvaged, in some cases, if an unplanned abort occurs. The valve on the vapour vent line is normally open. If the power fails the valve opens, releasing the pressure through the vapour line. The liquid drain line is normally closed retaining the liquid propane if the power fails. Since the vapour vent will have released the pressure and auto-refrigerated the tank-car to -40°C, the tank-car will be safe and a decision can be made on restarting the test or burning off the liquid. Both the vapour and liquid drain systems also have a manual valve that remains in the closed position until just prior to the test.

The power relay controlling the vapour vent valve is activated through the following controls:

- Manual toggle switch in control bunker – this must be closed to allow one of the following controls to close the valve.
- Normally open pushbutton in instrument bunker – for testing valve - pressing this button will close the valve.
- Computer controlled relay – closing the relay closes the valve.

- Toggle switch in the control bunker – closing the switch closes the valve.

The power relay controlling the liquid drain valve is activated by either of the following controls in parallel:

- Manual toggle switch in control bunker – closing the switch opens the valve.
- Normally open pushbutton in instrument bunker – for testing valve pressing this button will open the valve.

If the control power supply, or all electrical power, fails the power relay opens, cutting of power to the valves. The vapour vent valve then opens and the liquid drain closes. The action of the liquid drain valve is summarised in Table 35, and the vapour vent in Table 36.

The fuel control system is operated by the computer, but can be overridden manually. The fuel control valve is normally closed so that if power fails it will close and stop the flow. The fuel pump will stop operating if the power fails.

The power relays controlling the valve and fuel pump are activated through the following controls in series:

- Manual toggle switch in control bunker – this must be closed to open valve/run pump.
- Normally open computer controlled relay – this must be closed to open valve/run pump.
- For the fuel pump a normally open switch on the valve power relay – this must be closed to run pump to prevent pump operating with valve closed.

If the control electrical supply fails the power relay opens, cutting power to the valve, which closes, and pump, which shuts down. If the power electrical supply fails then the valve closes and the pump stops. The action of the fuel valve is summarised in Table 37 and the fuel pump in Table 38.

The water supply system is operated by the computer. This system is not critical to test control and can be shut down by either the pump or valve so no manual control is provided. Both the valve and pump are controlled through the computer. The valve relay must be activated before the pump relay.

The ignition system and calorimeter pumps are controlled through the computer. They will be on/off switches in the DAC program. The DAC board outputs then activate the power relays. The ignition system requires a relay for the fuel valve and the spark igniter. The calorimeter requires a relay to activate each pump. Manual control is included to activate remote still cameras. The cameras are activated by the following controls in parallel:

- Manual toggle switch in control bunker – when closed cameras are activated.
- Manual momentary pushbutton in control bunker – when pressed cameras are activated to allow for single shots of test.

Table 35: Control status for liquid drain valve

Operating Power	Control Power	Instrument Bunker Pushbutton	Control Bunker Toggle Switch	Valve Position
Off	On/off	Open/Close	Open/Close	**Close**
On	Off	Open/Close	Open/Close	**Close**
On	On	Close	Open/Close	**Open**
On	On	Open/Close	Close	**Open**
On	On	Open	Open	**Close**

Note: Pushbutton is normally open

Table 36: Control status for vapour vent valve

Operating Power	Control Power	Instrument Bunker Pushbutton	Control Bunker Toggle Switch 5	Control Bunker Toggle Switch 6	Computer Controlled Relay	Valve Position
Off	On/off	Open/Close	Open/Close	Open/Close	Open/Close	**Open**
On	Off	Open/Close	Open/Close	Open/Close	Open/Close	**Open**
On	On	Open/Close	Open	Open/Close	Open/Close	**Open**
On	On	Open/Close	Close	Close	Open/Close	**Close**
On	On	Open/Close	Close	Open/Close	Close	**Close**
On	On	Close	Close	Open/Close	Open/Close	**Close**

Note: Pushbutton is normally open

Table 37: Control status for fuel supply valve

Operating Power	Control Power	Computer Controlled Relay	Control Bunker Toggle Switch 3	Control Bunker Toggle Switch 4	Valve Position
Off	On/off	Open/Close	Open/Close	Open/Close	**Close**
On	Off	Open/Close	Open/Close	Open/Close	**Close**
On	On	Open/Close	Open	Open/Close	**Close**
On	On	Open/Close	Close	Close	**Open**
On	On	Close	Close	Open/Close	**Open**

Note: Computer controlled relay is normally open

Table 38: Control status for fuel pump

Operating Power	Control Power	Fuel Valve Relay	Computer Controlled Relay	Control Bunker Toggle Switch 1	Control Bunker Toggle Switch 2	Pump Status
Off	On/off	Open/Close	Open/Close	Open/Close	Open/Close	**Off**
On	Off	Open/Close	Open/Close	Open/Close	Open/Close	**Off**
On	On	Open/Close	Open/Close	Open	Open/Close	**Off**
On	On	Open/Close	Open/Close	Close	Close	**On**
On	On	Close	Close	Close	Open/Close	**On**
On	On	Open/Close	Open	Open/Close	Open	**Off**
On	On	Open	Open/Close	Open/Close	Open	**Off**

Note: Computer controlled relay and fuel valve relay are normally open

The ladder logic diagrams for low voltage circuit, used to actuate the power relays, and for the 120V operating circuit are given in Figure 50. The diagrams for camera, calorimeter pump and fuel pump operation are shown in Figure 51. The control system is summarised in Boolean algebra below:

$$\text{Vapour vent valve} = P_o \cdot P_c \cdot (PB_1 + RC_3 + S_6) \cdot S_5$$

$$\text{Liquid drain valve} = \overline{P_o \cdot P_c \cdot (PB_2 + S_7)}$$

$$V_F = \overline{P_o \cdot P_c \cdot (RC_2 + S_4) \cdot S_3}$$

$$\text{Fuel Pump} = P_o \cdot P_c \cdot (V_F \cdot RC_1 + S_2) \cdot S_1$$

$$\text{Spark Igniter} = RC_4$$

$$\text{Ignition fuel valve} = \overline{RC_5}$$

$$\text{Calorimeter pumps} = RC_{6,7,8}$$

$$V_W = RC_{10}$$

$$\text{Water Pump} = \mathrm{V_W} \cdot RC_9$$

V_F = Fuel supply valve

1 = Valve closed

0 = Valve open

$\mathrm{P_o}$ = Operating power (0 = Off, 1 = On)

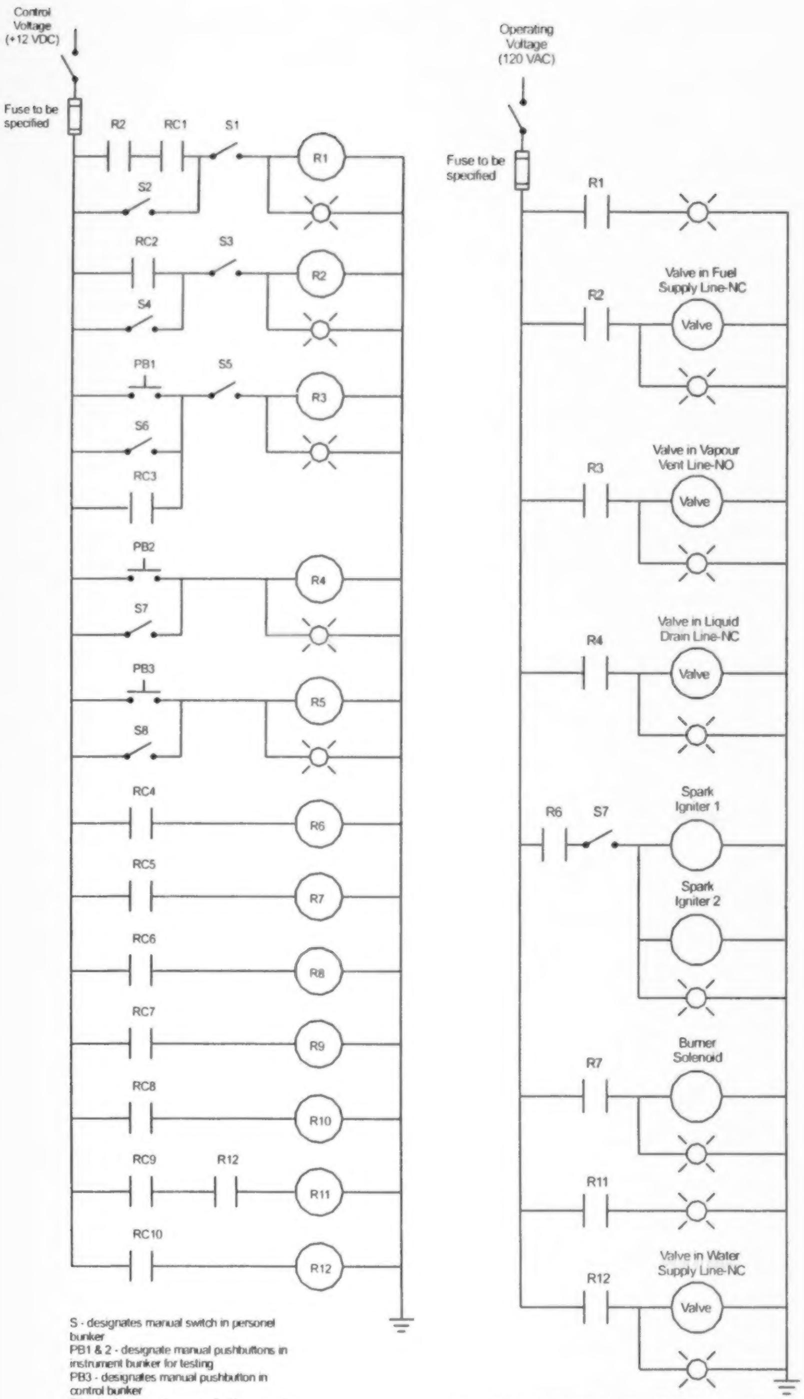
$\mathrm{P_c}$ = Control power (0 = Off, 1 = On)

PB = Push button in instrument bunker (0 = Open, 1 = Closed)

S = Toggle switch in personnel bunker (0 = Open, 1 = Closed)

RC = Computer controlled relay (0 = Not powered, 1 = Powered)

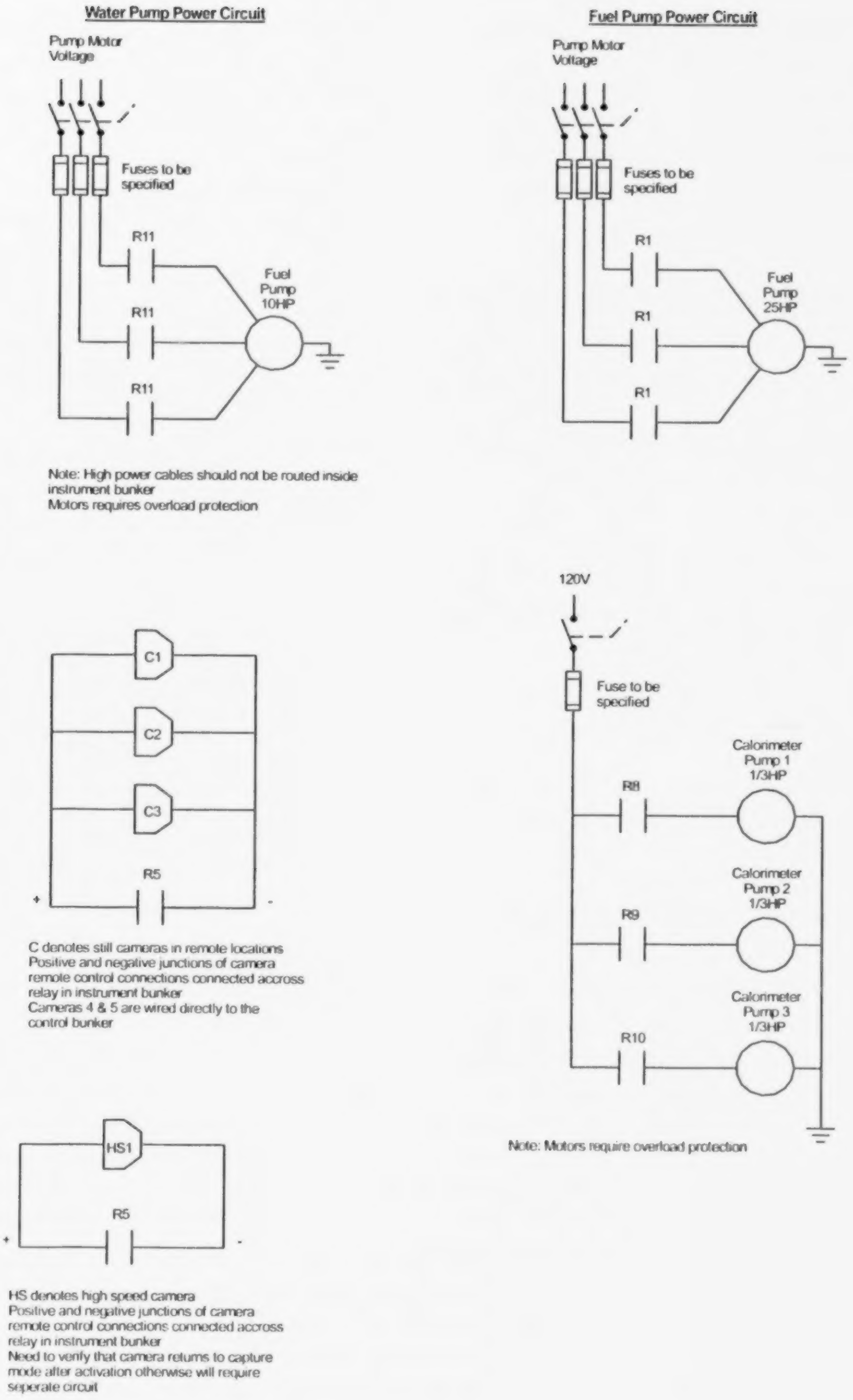
Numbering relays, switches and pushbuttons corresponds to control diagram


Control Voltage (+12 VDC)
Fuse to be specified
R2
RC1
S1
R1
S2
RC2
S3
R2
S4
PB1
S5
R3
S6
RC3
PB2
R4
S7
PB3
R5
S8
RC4
R6
RC5
R7
RC6
R8
RC7
R9
RC8
R10
RC9
R12
R11
RC10
R12
Operating Voltage (120 VAC)
Fuse to be specified
R1
R2
Valve in Fuel Supply Line-NC
Valve
R3
Valve in Vapour Vent Line-NO
Valve
R4
Valve in Liquid Drain Line-NC
Valve
R6
S7
Spark Igniter 1
Spark Igniter 2
R7
Burner Solenoid
R11
R12
Valve in Water Supply Line-NC
Valve

S - designates manual switch in personel bunker
PB1 & 2 - designate manual pushbuttons in instrument bunker for testing
PB3 - designates manual pushbutton in control bunker
RC - desigantes relay controlled by computer DAC system
Indicator lights are in control bunker
Relays are in instrument bunker except R1, R8, R9, R10, R11 which are in field near pumps

Controls in instrument bunker except for R1, R11 and S7
R1 and R11 are near fuel and water pumps
S7 is in field in sight of burners
120V cables should be shielded

Figure 50: Ladder logic control diagram showing control circuit and 120V operating circuit



Water Pump Power Circuit
Pump Motor Voltage
Fuses to be specified
R11
R11
R11
Fuel Pump 10HP
Fuel Pump Power Circuit
Pump Motor Voltage
Fuses to be specified
R1
R1
R1
Fuel Pump 25HP
C1
C2
C3
R5
+
-
120V
Fuse to be specified
R8
Calorimeter Pump 1 1/3HP
R9
Calorimeter Pump 2 1/3HP
R10
Calorimeter Pump 3 1/3HP
HS1
R5
+
-

Note: High power cables should not be routed inside instrument bunker
Motors requires overload protection

C denotes still cameras in remote locations
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Cameras 4 & 5 are wired directly to the control bunker

Note: Motors require overload protection

HS denotes high speed camera
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Need to verify that camera returns to capture mode after activation otherwise will require seperate circuit

Figure 51: Ladder logic control diagram showing camera and pump operating circuits

11.3. Computer Control System

The computer control system operates components, which test safety does not depend on, without manual backup. It also controls the fuel flow which requires constant monitoring and control. The fuel flow requires a manual back up, since the ability to control it must not be lost (see the section 11.2). This section explores the logic required to activate the computer controlled relays, to see how they fit into the entire control system refer to section 11.2. Table 39 summarises the components controlled by the computer and whether they have a manual backup.

Table 39: Computer controlled system components

System	Component	Relay	Manual Backup
Fuel Delivery	Fuel Pump	RC1	Yes
	Fuel Valve	RC2	Yes
Water Delivery	Water Pump	RC9	No
	Water Valve	RC10	No
Vapour Vent	Vent Valve	RC3	Yes
Pool Fire Ignition	Spark Igniters (2)	RC4	No
	Propane Supply Valve	RC5	No
Calorimeters	Pump 1	RC6	No
	Pump 2	RC7	No
	Pump 3	RC8	No

The computer controlled relays will be activated by the TTL (transistor-transistor logic) outputs from the DAC board. These low power relays in turn activate the high power control relays.

11.3.1. Fuel Delivery Control System

The object of the fuel delivery control system is to maintain the fuel level in the pan between the specified levels and prevent overflow. Redundancy is included to reduce the chances of a serious error. Table 40 summarises the inputs and outputs required for fuel flow control. Primary control is dictated by the depth gauge and the level thermocouples provide verification and backup. Figure 52 is a flow chart showing the logic involved in controlling the fuel level. Control can be transferred to the thermocouples if it is believed the depth gauge is malfunctioning. The depth gauge has errors due to the difference in density of fuel and water, and the thermocouples have errors due to boiling of the fuel.

If control is transferred, and for verification of the depth gauge, the limit thermocouples are used to determine if the upper and lower levels have been reached. The procedure is identical for the upper and lower limit thermocouples, and is given in Figure 53. The fuel level is assumed above the thermocouple when they are cool and below it when they are hot. The border between cool and hot was set to 450°C because it is 150°C above the expected maximum boiling point of JP-4, but well below the fire temperature. A 150°C buffer above the listed boiling point was used to allow for variations in JP-4 composition and errors in the system. Above 450°C the fluid level is assumed to be below the thermocouple and below 450°C the fluid is assumed to be above the thermocouple.

The overflow inputs are final checks to ensure the fire pan does not spill. The overflow level from the depth gauge is set below the overflow thermocouple. If the overflow level, from the depth gauge, is triggered the full fuel shut down procedure is followed. If the overflow thermocouple is triggered both the pump and valve are immediately stopped. The logic for this is outlined in Figure 54.

Table 40: Required inputs and outputs for computer control of fuel delivery

Device	Range	In/Out	Symbol
Depth Gauge	Depth	Input	D
Level Sump Thermocouple	Temperature	Input	ST
Fire Pan Water Thermocouple	Temperature	Input	PT
Lower Limit Thermocouple 1	Temperature	Input	LLT1
Lower Limit Thermocouple 2	Temperature	Input	LLT2
Upper Limit Thermocouple 1	Temperature	Input	ULT1
Upper Limit Thermocouple 2	Temperature	Input	ULT2
Overflow Thermocouple	Temperature	Input	OT
Pump Relay	On/Off	Output	RC1
Valve Relay	On/Off	Output	RC2

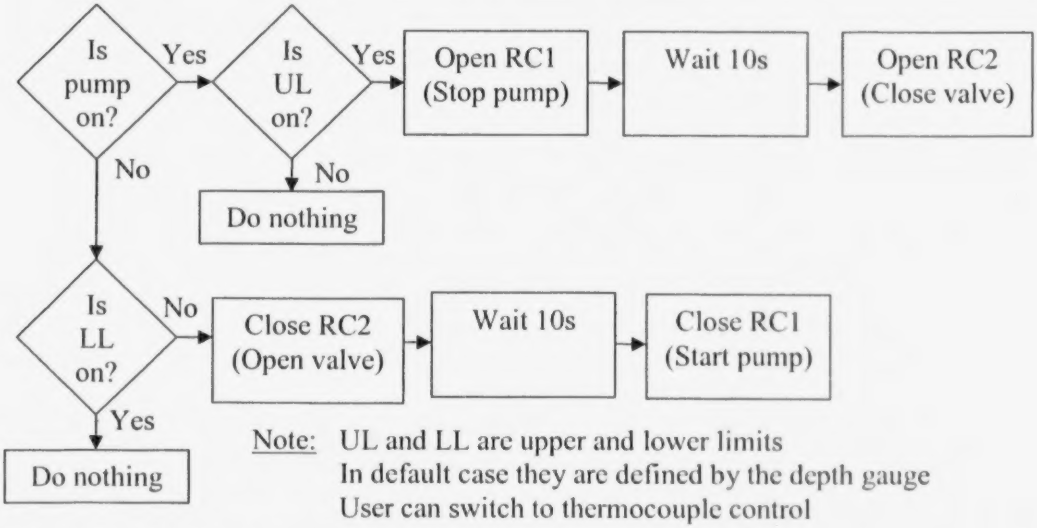
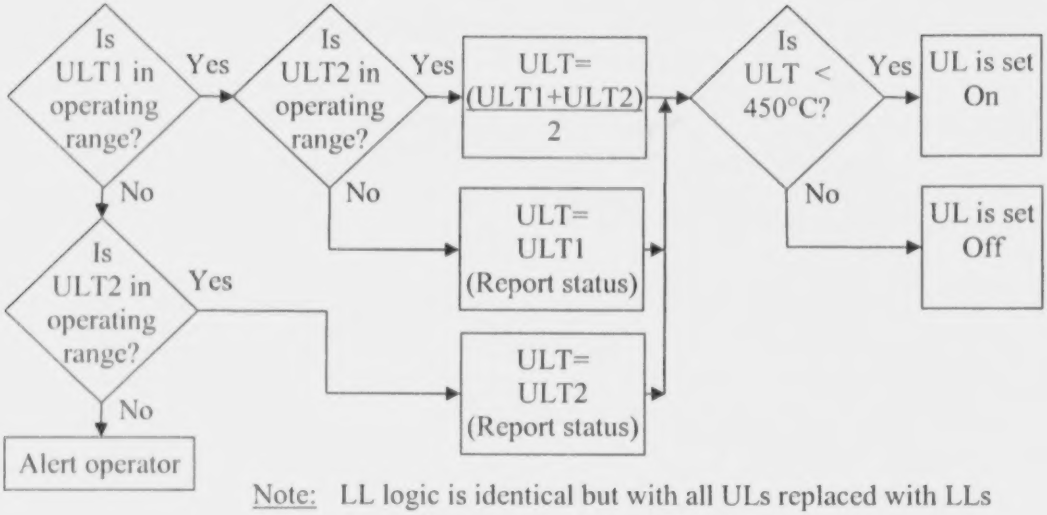

Is pump on?
Yes
Is UL on?
Yes
Open RC1 (Stop pump)
Wait 10s
Open RC2 (Close valve)
No
No
Do nothing
Is LL on?
No
Close RC2 (Open valve)
Wait 10s
Close RC1 (Start pump)
Yes
Do nothing
Note: UL and LL are upper and lower limits
In default case they are defined by the depth gauge
User can switch to thermocouple control

Figure 52: Fuel level control diagram


Is ULT1 in operating range?
Yes
No
Is ULT2 in operating range?
Yes
No
ULT= (ULT1+ULT2) / 2
ULT= ULT1 (Report status)
Is ULT2 in operating range?
Yes
No
ULT= ULT2 (Report status)
Alert operator
Is ULT < 450°C?
Yes
No
UL is set On
UL is set Off

Note: LL logic is identical but with all ULs replaced with LLs
Operating range is 0°C to 2000°C

Figure 53: Level limit setting using thermocouples

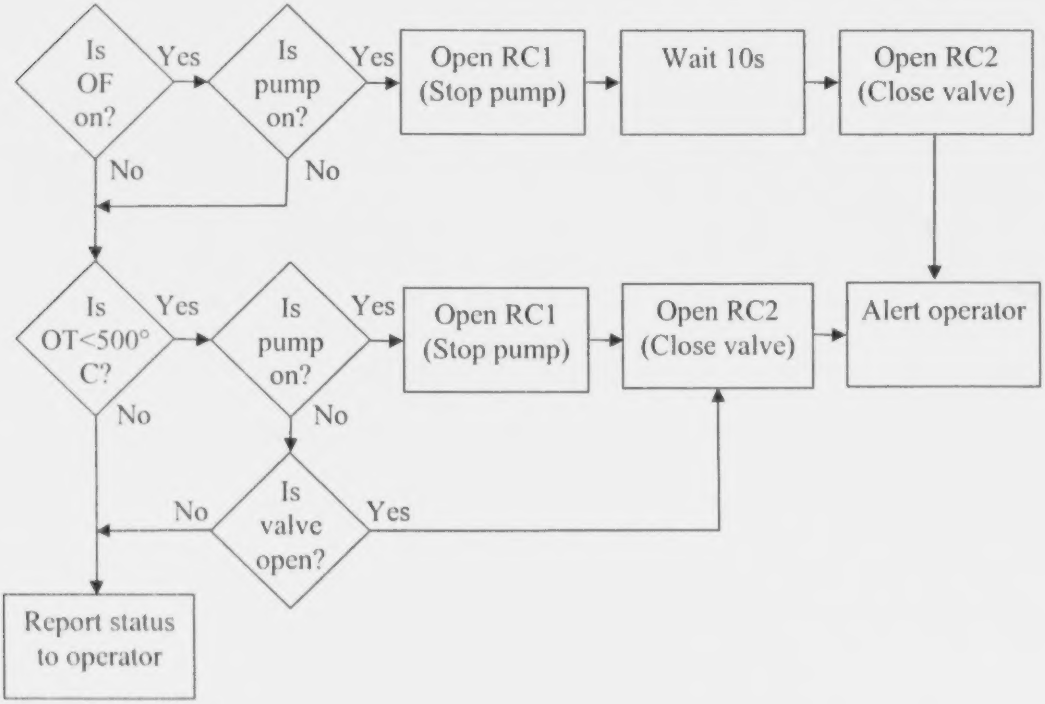

Is OF on?
Yes
No
Is pump on?
Yes
No
Open RC1 (Stop pump)
Wait 10s
Open RC2 (Close valve)
Is OT<500° C?
Yes
No
Is pump on?
Yes
No
Open RC1 (Stop pump)
Open RC2 (Close valve)
Alert operator
Is valve open?
No
Yes
Report status to operator

Figure 54: Fuel overflow control system

The temperature in the level sump will remain almost constant during the test, while the fire pan water temperature will approach 100°C. The difference in density will cause the sump depth, for a given fire pan depth, to change. The initial sump level will differ from the fire pan level due to the presence of JP-4 in the fire pan, which is less dense than water. This will be compensated for by the control system. The initial sump depth will be measured, during the filling process, at each control level. The change in sump depth from the initial, for a given fire pan depth is then given by equation 1. This assumes that the mass of water in the fire pan is constant and that the sump and fire pan water are initially at the same temperature. It does not account for boil over, which reduces the mass of water and increases the depth of fuel.

$$\Delta h_{sump} = h_{w,i}\left(\frac{\rho_{w,i}}{\rho_s} + \frac{\rho_f}{\rho_s}\left(1 - \frac{\rho_{w,i}}{\rho_w}\right) - 1\right) + h_{f,i}\left(\frac{\rho_f}{\rho_s} - \frac{\rho_{f,i}}{\rho_s}\right) \tag{1}$$

$h_{w,i}$ = Initial height of water in fire pan
$h_{f,i}$ = Initial height of fuel in fire pan above water
$\rho_{w,i}$ = Density of water at initial temperature
$\rho_{f,i}$ = Density of fuel at initial temperature
ρ_s = Density of water in sump
ρ_w = Density of water in fire pan
ρ_f = Density of fuel

Table 41 provides the sump level set points and the corresponding fire pan depths for the lower limit, upper limit and overflow levels. The first three rows are the levels at initial conditions with all temperatures at 20°C. The next three show what happens when the fire pan water and fuel are heated to 100°C. The water depth, increases due to expansion, the fuel depth decreases, but the total depth remains constant. This system used the water temperature for both the fuel and water depth. If the fuel is heated to its boiling point, the fire pan depths in the next three rows result. The largest error is in the overflow which increases 2.6 cm beyond the desired level, but is still below the thermocouple overflow shutdown level. Accuracy could be improved by using the lower limit thermocouple temperature, when the upper limit thermocouple is immersed, for the fuel temperature.

Evaporation of the water creates a larger error due to the lower density of fuel filling the space previously occupied by the water. As the water evaporates it is replaced by fuel, which requires a greater depth than water to achieve the same head. The last three rows of Table 41 show the depths if the fuel is heated to its boiling point and 150 mm (the maximum possible water level drop due to evaporation if the make up water pump is not functioning) has occurred.

Even the upper limit level exceeds the height of the fire pan. Using the actual fuel temperature to calculate the sump depth only corrects the upper limit to the top level of the fire pan. At this level the upper limit thermocouple will be clearly immersed and it could be used to control fuel flow. The reduced accuracy due to boiling would still be better than the error in the sump due to evaporation.

Table 41: Comparison of sump and fire pan liquid levels

Sump Depth (m)	Drop in Sump Level (m)	Water Temp. (°C)	Fuel Temp. (°C)	Water Depth (m)	Fuel Depth (m)	Fire Pan Depth (m)	Condition
0.640	0	20	20	0.600	0.050	0.650	Initial LL level
0.680	0	20	20	0.600	0.100	0.700	Initial UL level
0.704	0	20	20	0.600	0.130	0.730	Initial OF level
0.619	0.021	100	100	0.625	0.025	0.650	Heated LL level
0.656	0.024	100	100	0.625	0.075	0.700	Heated UL level
0.678	0.026	100	100	0.625	0.105	0.730	Heated OF level
0.619	0.021	100	300	0.625	0.031	0.656	LL level with hotter fuel
0.656	0.024	100	300	0.625	0.094	0.719	UL level with hotter fuel
0.678	0.026	100	300	0.625	0.131	0.756	OF level with hotter fuel
0.619	0.021	100	100	0.475	0.219	0.694	LL level with 150 mm evaporation
0.656	0.024	100	100	0.475	0.269	0.744	UL level with 150 mm evaporation
0.678	0.026	100	100	0.475	0.299	**0.774**	OF level with 150 mm evaporation
0.619	0.021	100	300	0.475	0.274	0.749	LL level with 150 mm evaporation and hotter fuel
0.656	0.024	100	300	0.475	0.336	**0.811**	UL level with 150 mm evaporation and hotter fuel
0.678	0.026	100	300	0.475	0.374	**0.849**	OF level with 150 mm evaporation and hotter fuel

Note: Bold fire pan depths indicate thermocouple overflow shutdown is triggered prior to reaching that level

11.3.2. Water Delivery Control System

Water delivery is activated by the conductivity meter in the fire pan. When the conductivity drops to zero fuel is assumed to be present and make up water is required. The water pump is activated for a set period of time to return the water level to its initial setting. With a 15L/s pump this will require 7.2 minutes. This value can be adjusted to account for boil off, but should not exceed 19.2 minutes, the time required to fill the pan to the lower fuel limit. The lower limit thermocouple should be used as a check on the water level. If boil off is occurring the fuel will have exceeded 100°C and if the lower limit thermocouple drops to 100°C the water flow must be stopped.

11.3.3. Calorimeters, Ignition and Vapour Vent

The ignition system and vapour vent valve are both operator controlled. An option on the DAC display will allow the activation of the following functions:

- Open vapour vent valve – computer will prompt for verification of action
- Start spark igniters
- Open propane fuel valve to ignition system
- Computer will prompt for verification of action before allowing both spark igniters and propane to be activated

The vapour vent valve will have a separate program to control it during the fill process to allow for tank-car purging. This procedure is discussed in section 3.2. During the test the vapour vent valve is under operator control only.

The calorimeters will be activated by the operator. The computer will provide time for the pumps to start and then begin monitoring the flow through the calorimeters. If the flow stops the computer will shut down the pump and alert the user. This is to protect the pump from damage. Table 42 summarises the input and outputs required for control of these elements.

Table 42: Required inputs and outputs for computer control of calorimeters, ignition and vapour vent

Device	Range	In/Out	Symbol
Calorimeter 1 Flow Meter	Flow Rate	Input	
Calorimeter 2 Flow Meter	Flow Rate	Input	
Calorimeter 3 Flow Meter	Flow Rate	Input	
Calorimeter Pump 1	On/Off	Output	RC6
Calorimeter Pump 2	On/Off	Output	RC7
Calorimeter Pump 3	On/Off	Output	RC8
Vapour Vent Valve Relay	On/Off	Output	RC3
Spark Igniter Relay	On/Off	Output	RC4
Propane Valve Relay	On/Off	Output	RC5

11.3.4. Real-Time Rupture Prediction

The data from the tank-car will also be used to estimate the time remaining until the tank-car fails, which can be used to decide to abort the test. Software will produce real time predictions, using temperatures and pressures measured on the tank-car. This will provide the test director with a continuously updated estimate of the time until the tank-car fails.

The predictions will be based on the high temperature stress rupture work of Birk and Yoon (2006). The accumulated damage to the tank car is calculated based on the stress rupture failure criterion, given below:

$$SR = \int_{\text{Time in fire}} \frac{dt}{t_f} \qquad 2$$

$$t_f = \left(\frac{\sigma}{K_1 - K_2 T} \right)^{1/(K_3 - K_4 T)}$$

σ = Stress 3

$K_{1,2,3,4}$ = Material specific constants

T = Temperature

When the stress rupture failure criterion exceeds SR=1 the tank-car will fail. The temperature will be determined from select groups of temperatures on the tank-car wall, and the stress calculated from the tank-car pressure and nominal wall thickness. Data filtering techniques may be required to reduce the random variation in the results, but this will have to be carefully handled to avoid creating a delay in the prediction. The prediction will be performed by projecting the stress rupture failure criterion forward in time, with a forecasting technique. The time at which SR reaches one will be the time of failure.

12. Conclusions and Recommendations

A plan has been devised for engulfing fire testing of thermally protected 112J type rail tank-cars filled with LPG or propane. The main objective of the test is to provide detailed thermal data for modern thermally protected rail tank-cars subjected to engulfing fires. This data is needed for further development and validation of tank-car thermal models. A secondary objective is to provide data for tanks with thermal protection defects.

This document provides a basis for the final test plan and design, to be completed once the test location, objectives and resources are fully specified. The plan is designed to obtain the maximum value from the tests by instrumenting the tank, fire and surroundings to understand the system behaviour during an engulfing liquid hydrocarbon pool fire.

The proposed fire and tank instrumentation allows for detailed measurement of fire, lading, wall and jacket temperatures, and tank pressure. The fire and jacket temperature data will provide a much more detailed understanding of the fire conditions than we had from previous fire tests. Knowing the true fire conditions is critical for thermal model validation.

If all goes as planned, no tank-car ruptures are expected in this test series. The data acquisition and control system has been designed to include a real-time failure analysis based on high-temperature stress rupture. This system would be used to predict the time remaining until tank failure during each test. This could help decide when to abort a test in order to avert an impending tank failure. Test conditions most likely to result in a rupture will be performed in the last test of the series. If the final test does end in a rupture, field instrumentation should be in place to measure the blast and thermal hazards.

The proposed control system specifies manual overrides for any critical functions, such as fuel flow and tank-car vent lines. Having secondary manual controls will reduce the likelihood that a test will be completely lost in the event a failure occurs in the primary computer control system.

The level of detail provided in this proposed plan should allow for the expedient determination of final test details, including:

- procedures for filling, testing and safety responses
- scheduling
- human and physical resource requirements
- detailed drawings for all mechanical components
- site set up details
- instrumentation details
- data acquisition and control software programming

It should be emphasized that the likelihood of successful completion of the test program will depend to a large degree on the experience and capabilities of those chosen to execute it. This will be especially true for issues related to safety, system controls, data acquisition and analysis of the test results.

This report has brought the design to the stage where purchasing of components and programming of software can begin. Software development for data acquisition and control should be initiated as early in the project schedule as possible to help prevent any delays or unexpected problems when the test site is available for use. Once the test site geography is known, many test details can be finalized. Existing facilities and resources at the test site will have a significant impact on the final design, as will the resources committed to the project by the sponsors.

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Appendix A: Drawing Package

Some, but not all, of the drawings in this appendix appear as figures in the report. The figures in the report are not to a standard scale, and in the case of a discrepancy between the figures and drawing the drawing should be taken as correct. The drawings in this appendix are close to the scale listed on them, but errors due to copying between programs may have resulted in small discrepancies.

Each drawing produced for this report has a unique drawing number defined by the following key:

Drawing number format: XX-YY-ZZ-00

XX - Project reference - "RT" for Rail tank-car Test for all drawings
YY – File drawing is saved in:
    CA – Cables.skf
    BU – Bunker.skf
    IW – Instrument Well.skf
    CL – Calorimeter.skf
    CT – Calorimeter Tank.skf
    RC – Robust Control.skf
    SC – Safe Control.skf
    CT – Control.skf
    DF – DFT.skf
    FP – Fire Pan.skf
    FT – Fire TC.skf
    PV – Pump Valve.skf
    SD – Site Detail.skf
    TF – Tank fittings.skf
    TT – Tank thermocouples.skf
    IG – Ignition.skf
ZZ – Designation for particular drawing
00 – Drawing version

All the drawings were produced in AutoSketch Vs. 9. The electronic version of the files is available in both AutoSketch and AutoCAD 2004 format, but AutoCAD files have not been checked for accuracy of conversion from AutoSketch. Some of the files contain more than one drawing and the file "Drawing Setups.doc" should be consulted for scale, page position and layer status for each drawing. Additional drawing files contain sketches included in the body of the report only. Table A-1 lists all the drawings contained in this package, the source file, drawing number and total number of sheets that make up the drawing.

Table A-1: Summary of drawing package

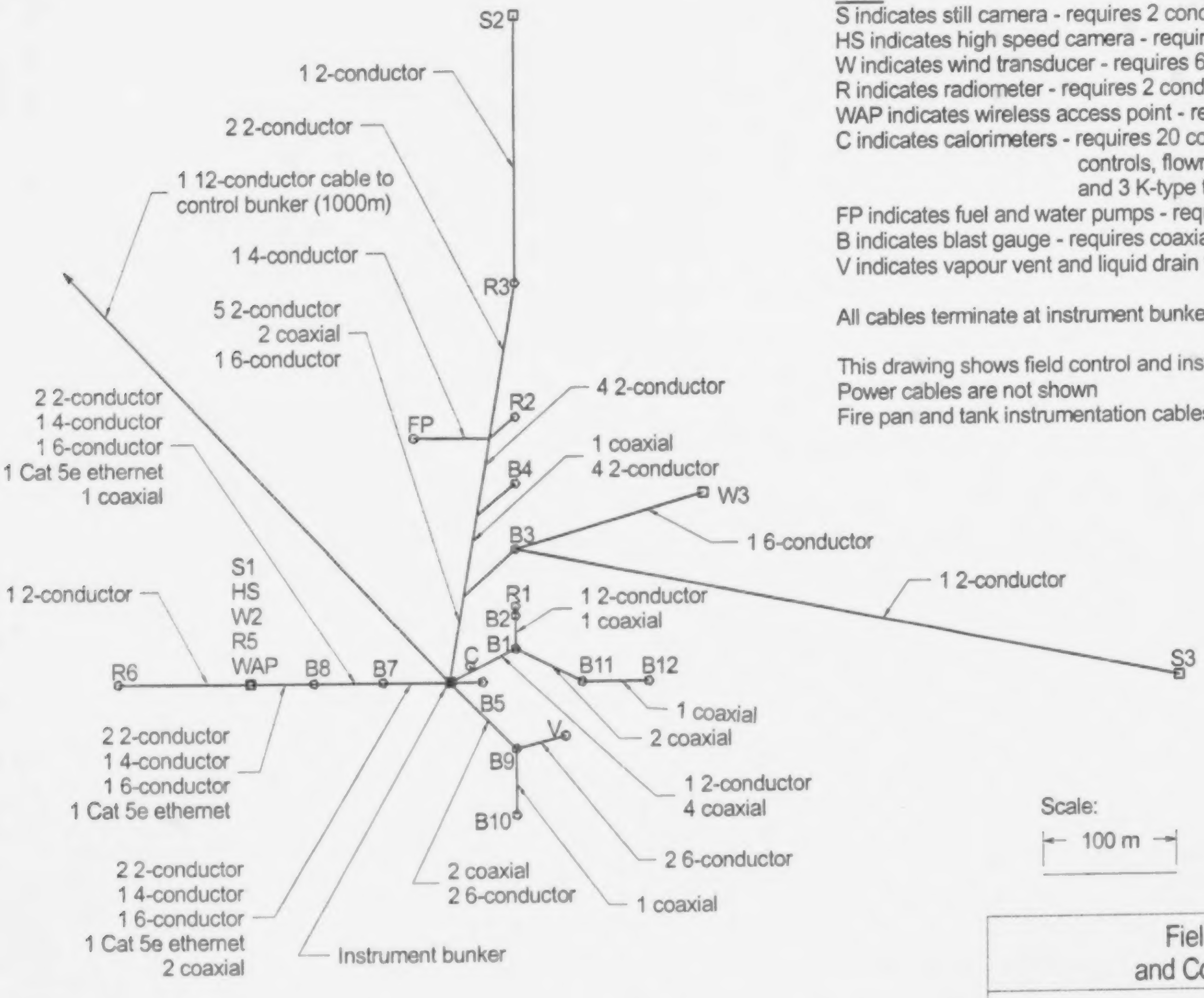
Drawing Name	File	Drawing Number	Sheets
Field Instrumentation and Control Cable Layout	Cables.skf	RT-CA-FC-01	1
Fire pan and Railcar Instrumentation and Control Cable Layout	Cables.skf	RT-CA-RC-01	1
Instrument Bunker Access and Protection	Bunker.skf	RT-BU-IB-01	2
Instrument and Connection Well	Instrument well.skf	RT-IW-IW-01	1
Fire Pan and Railcar Instrumentation And Control Cable Access Box	Instrument well.skf	RT-IW-AB-01	1
DFT Cable Exit from Fire Pan	Instrument well.skf	RT-IW-DE-01	1
Ground Preparation for Fire Pan	Instrument well.skf	RT-IW-GP-01	1
Calorimeter Section	Calorimeter.skf	RT-CL-CS-01	1
Calorimeter Schematic	Calorimeter.skf	RT-CL-CC-01	1
Wiring Diagram for Robust Test Control	Robust control.skf	RT-RC-RC-01	3
Wiring Diagram for Safe Test Control	Safe control.skf	RT-SC-SC-01	3
Wiring Diagram for Test Control	Control.skf	RT-CT-BC-01	3
Directional Fire Thermometer (DFT)	DFT.skf	RT-DF-DF-01	1
Fire Pan	Fire Pan.skf	RT-FP-FP-01	3
Level Well	Fire Pan.skf	RT-FP-LW-01	1
Railcar Support	Fire Pan.skf	RT-FP-RS-01	1
Fire Thermocouple and Directional Fire Thermometer Locations	Fire TC.skf	RT-FT-FT-01	1
Fire Pan Ignition System	Ignition.skf	RT-IG-IG-01	1
Seperate Fuel and Water Supply Pump and Valve Schematic	Pump Valve.skf	RT-PV-FW-01	1
Combined Fuel and Water Supply Pump and Valve Schematic	Pump Valve.skf	RT-PV-PV-01	1
Blast Gauge Positions	Site Detail.skf	RT-SD-BG-01	1
Radiometer Positions	Site Detail.skf	RT-SD-RD-01	1
Site Plan	Site Detail.skf	RT-SD-SP-01	2
Cross Section of Main Instrumentation Conduit	Site Detail.skf	RT-SD-IC-01	1
Additional Tank Fittings for Entry Into Instrument Well	Tank fittings.skf	RT-TF-IW-01	1
Railcar tank wall and shell thermocouple locations	Tank thermocouples.skf	RT-TT-WS-01	1
Insulation defect layout and thermocouple positions	Tank thermocouples.skf	RT-TT-ID-01	2

Drawing Name	File	Drawing Number	Sheets
Lading, wall and shell array thermocouples	Tank thermocouples.skf	RT-SD-IC-01	1

Note:
S indicates still camera - requires 2 condcutors
HS indicates high speed camera - requires 2 conductors
W indicates wind transducer - requires 6 conductors
R indicates radiometer - requires 2 condcutors
WAP indicates wireless access point - requires Cat 5e ethernet cable
C indicates calorimeters - requires 20 conductors total for pump
controls, flowmeters and ignition fuel solenoid,
and 3 K-type thermocouple pairs
FP indicates fuel and water pumps - require 4 conductors (2 each)
B indicates blast gauge - requires coaxial cable
V indicates vapour vent and liquid drain valves - requires 10 conductors

All cables terminate at instrument bunker

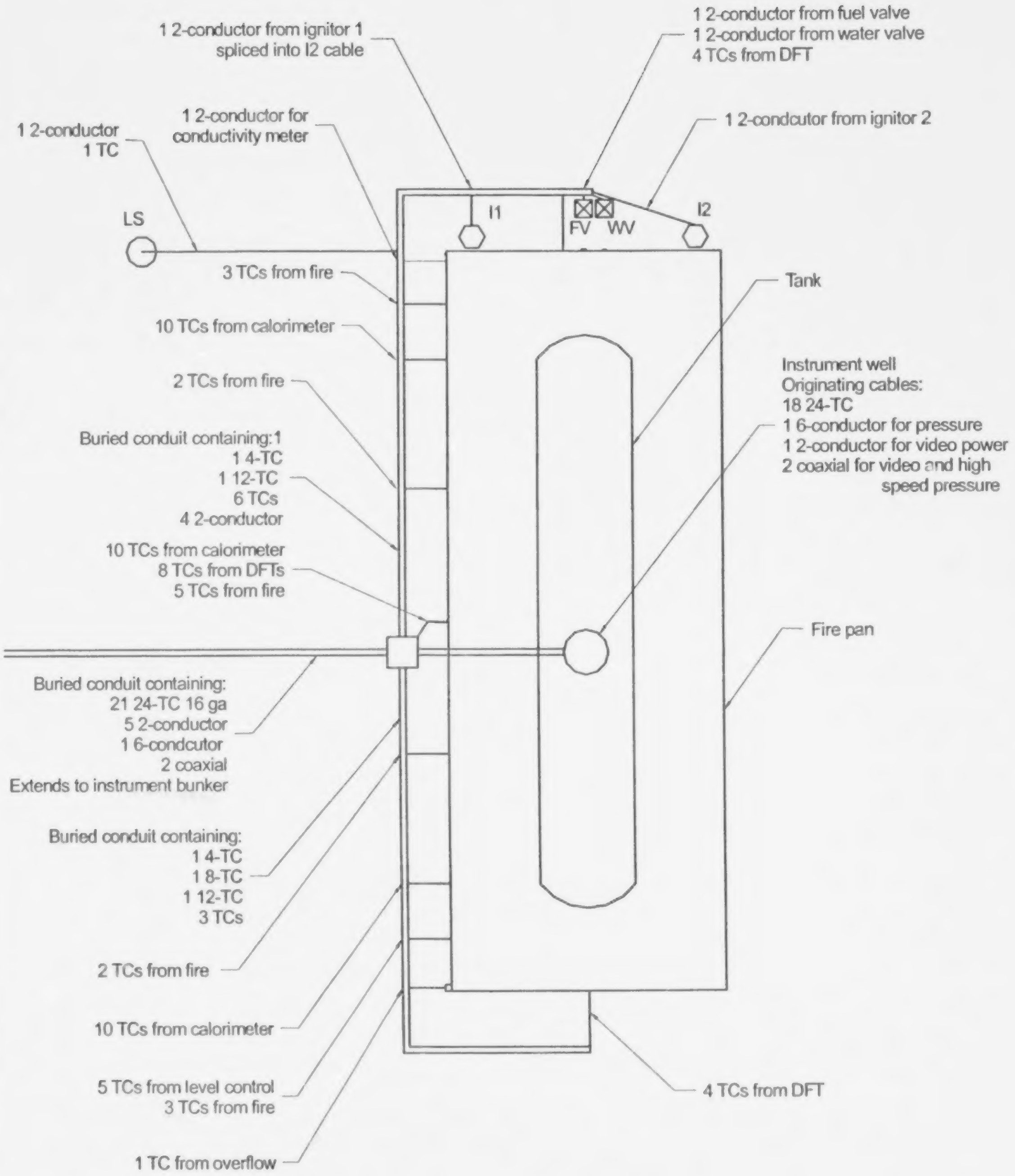
This drawing shows field control and instrumentation cable only
Power cables are not shown
Fire pan and tank instrumentation cables are shown on a seperate drawing


S2
1 2-conductor
2 2-conductor
1 12-conductor cable to
control bunker (1000m)
1 4-conductor
R3
5 2-conductor
2 coaxial
1 6-conductor
4 2-conductor
R2
FP
2 2-conductor
1 4-conductor
1 6-conductor
1 Cat 5e ethernet
1 coaxial
1 coaxial
4 2-conductor
B4
W3
1 6-conductor
B3
1 2-conductor
S1
HS
W2
R5
WAP
1 2-conductor
R1
B2
B1
1 2-conductor
1 coaxial
R6
B8
B7
C
B11
B12
S3
B5
1 coaxial
2 coaxial
2 2-conductor
1 4-conductor
1 6-conductor
1 Cat 5e ethernet
V
B9
1 2-conductor
4 coaxial
B10
2 6-conductor
2 2-conductor
1 4-conductor
1 6-conductor
1 Cat 5e ethernet
2 coaxial
2 coaxial
2 6-conductor
1 coaxial
Instrument bunker
Scale:
100 m

Cable Protection
Cables within 600m of tank muct be covered with earth
within 400m buried 2cm deep
witthin 150m buried 10cm deep
within 50m buried 30cm deep

Field Instrumentation and Control Cables Layout

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-CA-FC-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 22/08/06	Scale: 1:5000

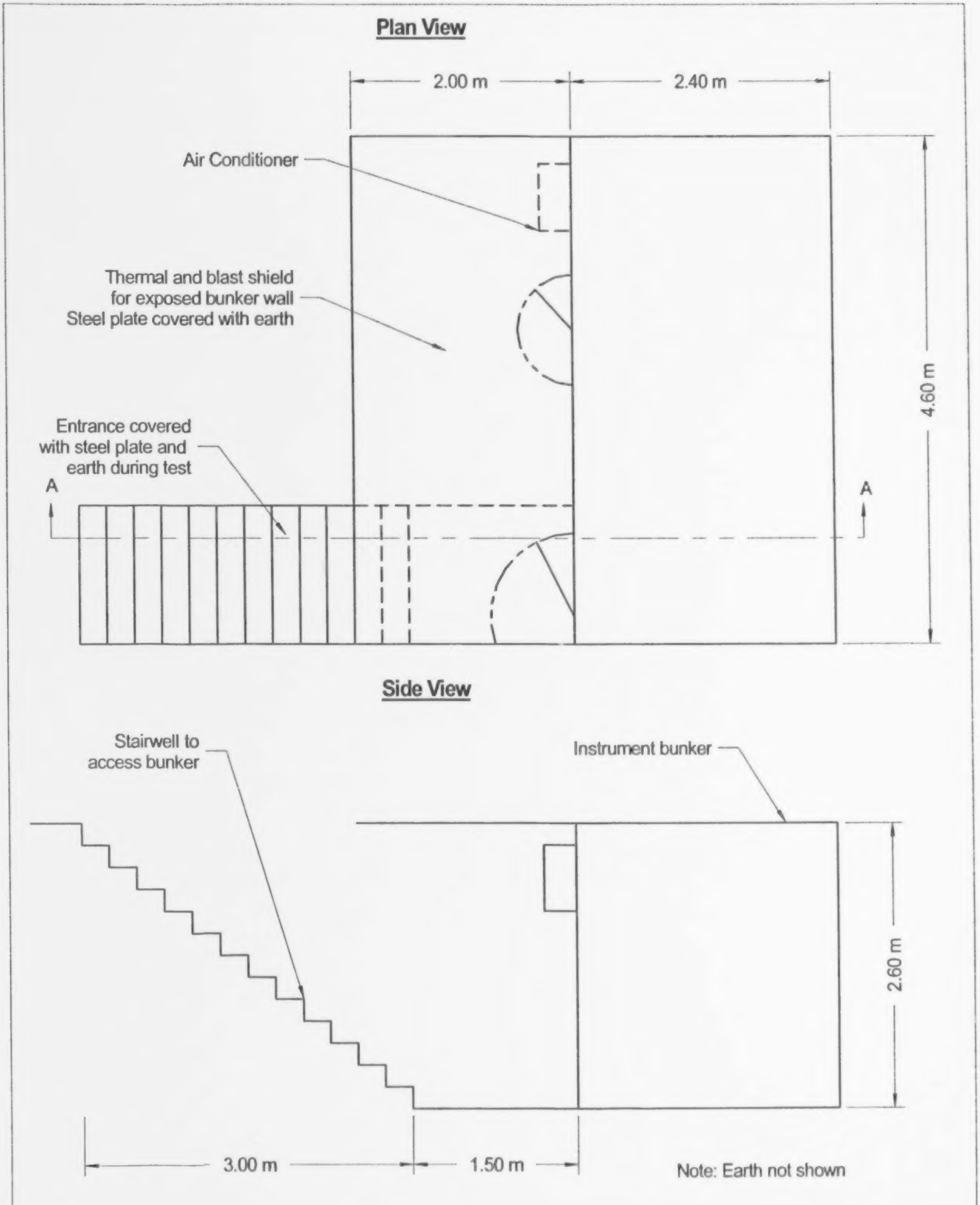

1 2-conductor from ignitor 1
spliced into I2 cable
1 2-conductor from fuel valve
1 2-conductor from water valve
4 TCs from DFT
1 2-conductor
1 TC
1 2-conductor for
conductivity meter
1 2-condcutor from ignitor 2
LS
I1
FV
WV
I2
3 TCs from fire
Tank
10 TCs from calorimeter
Instrument well
Originating cables:
18 24-TC
1 6-conductor for pressure
1 2-conductor for video power
2 coaxial for video and high
speed pressure
2 TCs from fire
Buried conduit containing:1
1 4-TC
1 12-TC
6 TCs
4 2-conductor
10 TCs from calorimeter
8 TCs from DFTs
5 TCs from fire
Fire pan
Buried conduit containing:
21 24-TC 16 ga
5 2-conductor
1 6-condcutor
2 coaxial
Extends to instrument bunker
Buried conduit containing:
1 4-TC
1 8-TC
1 12-TC
3 TCs
2 TCs from fire
10 TCs from calorimeter
4 TCs from DFT
5 TCs from level control
3 TCs from fire
1 TC from overflow

Note:

TC - designates 1 pair of K-type thermocouple wires
x-TC - designates a cable with x pairs of K-type thermocouple wires
x-conductor - designates cable with x copper conductors
DFT - indicates directional fire thermometer
I - indicates ignitor
FV - fuel valve
WV - water valve

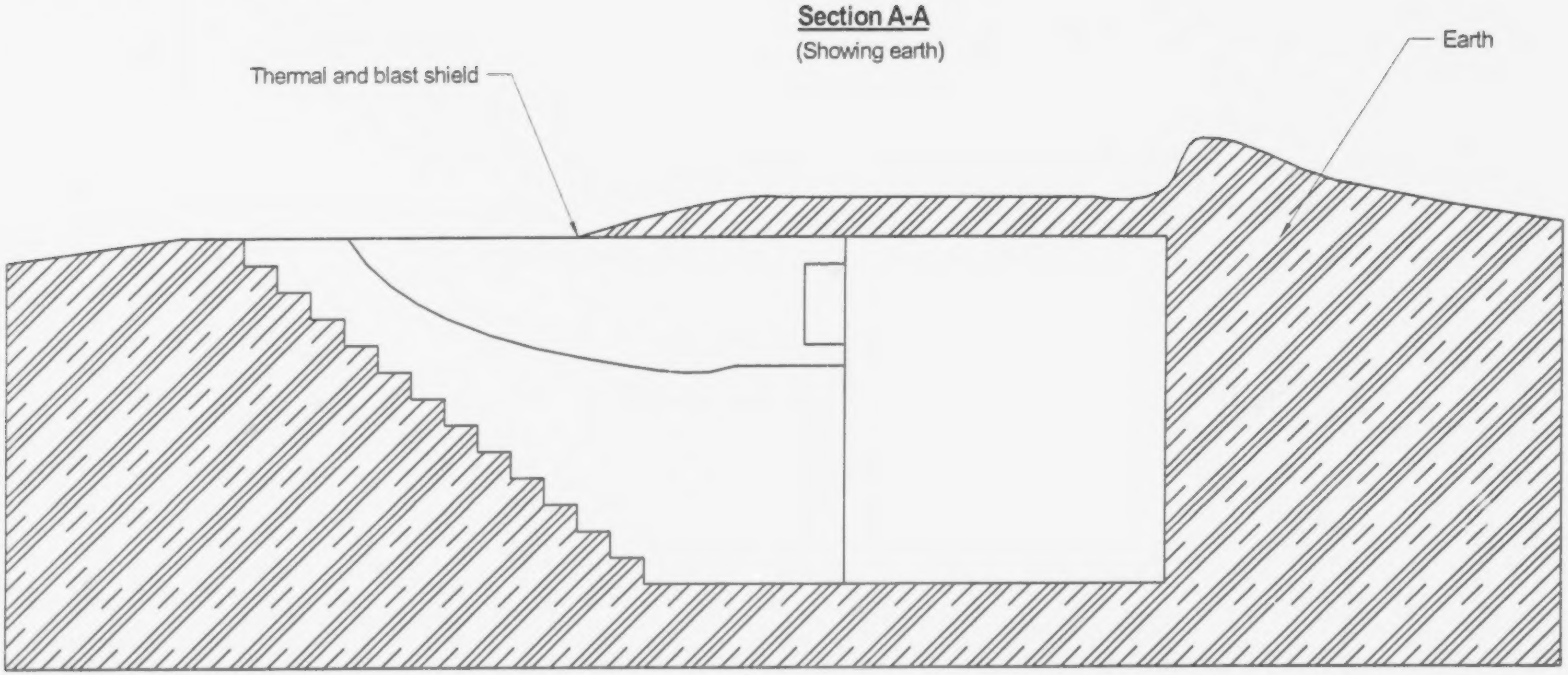
Fire Pan and Railcar Instrumentation
and Control Cables Layout

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-CA-RC-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 15/09/06	Scale: 1:200


Plan View
2.00 m
2.40 m
Air Conditioner
Thermal and blast shield
for exposed bunker wall
Steel plate covered with earth
4.60 m
Entrance covered
with steel plate and
earth during test
A
A
Side View
Stairwell to
access bunker
Instrument bunker
2.60 m
3.00 m
1.50 m
Note: Earth not shown

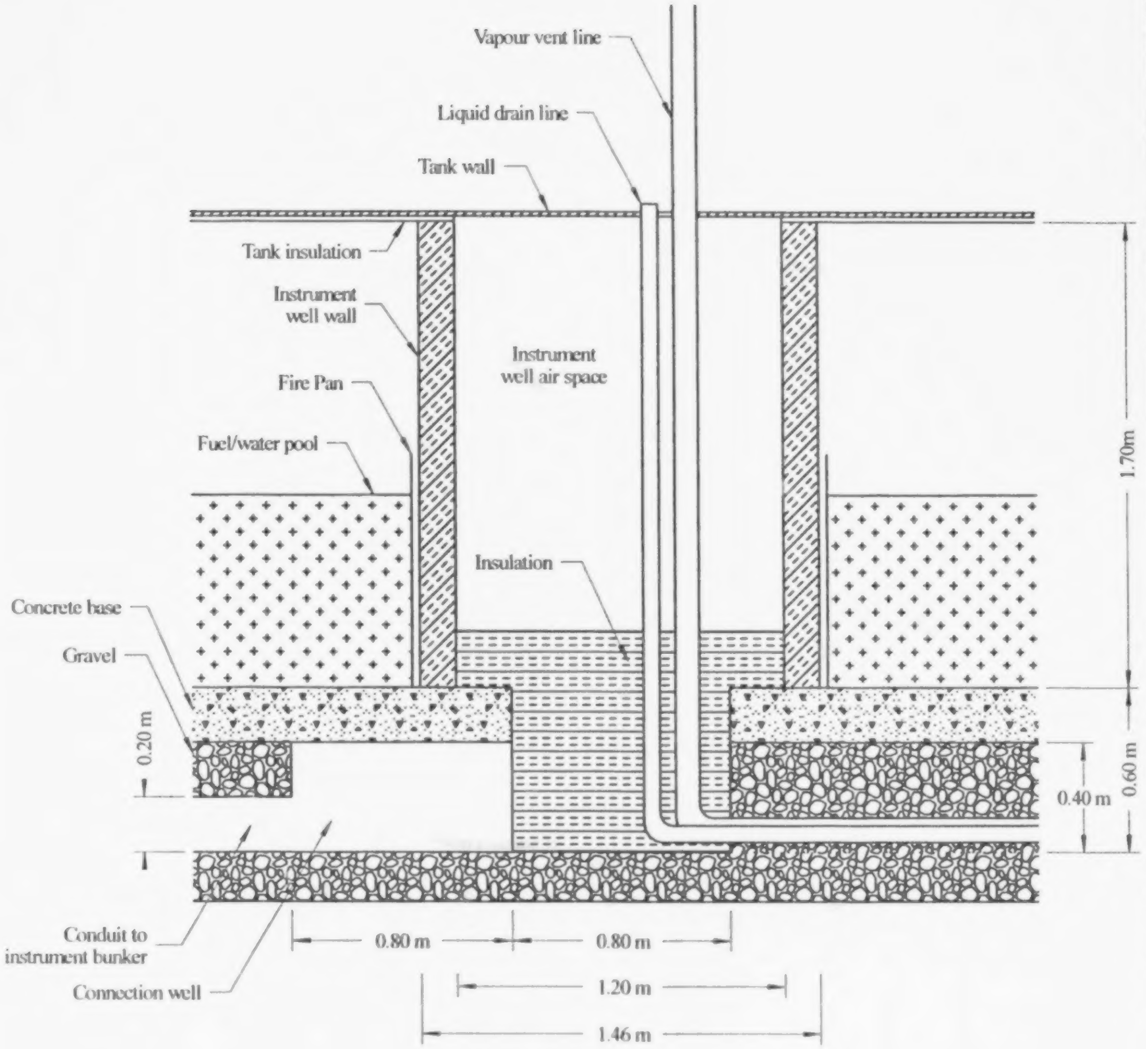
Instrument Bunker
Access and Protection

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-BU-IB-01	
	Vs.: 1	Sheet: 1 of 2
	Date: 04/08/06	Scale: 1:50

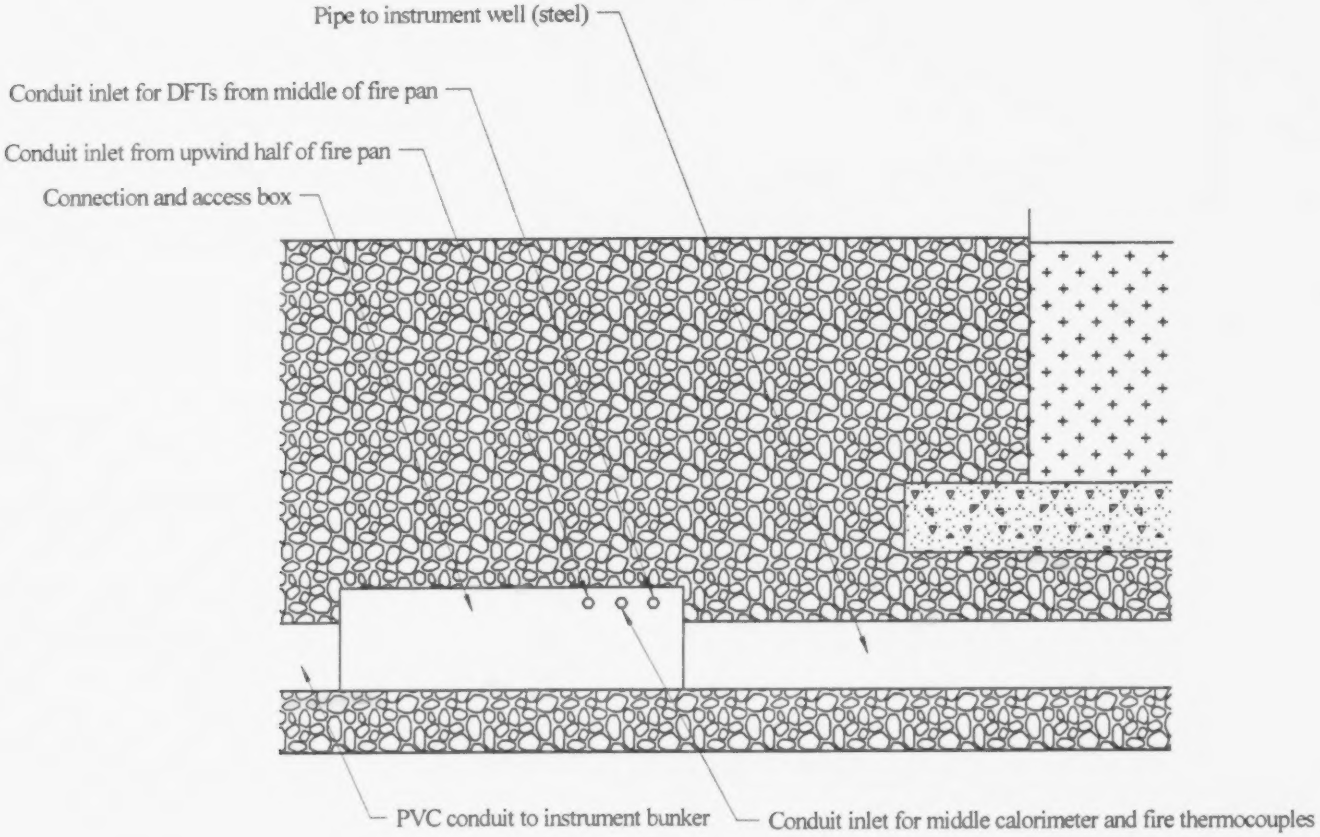

Section A-A
(Showing earth)
Thermal and blast shield
Earth

Instrument Bunker
Access and Protection

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-BU-IB-01	
	Vs.: 1	Sheet: 2 of 2
	Date: 04/08/06	Scale: 1:50

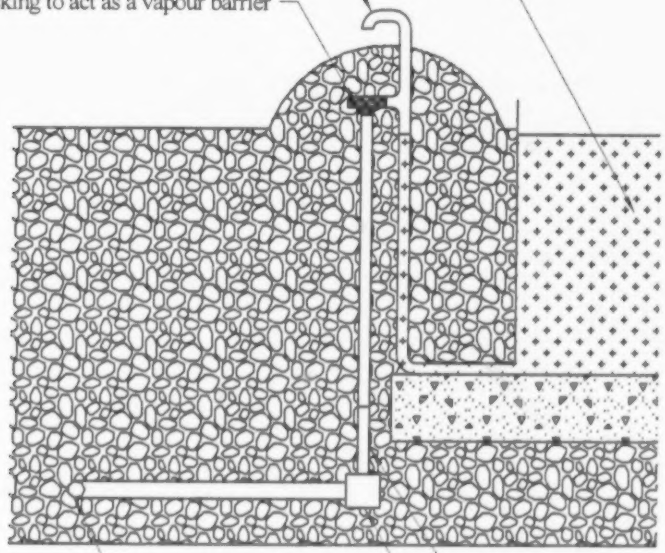

Vapour vent line
Liquid drain line
Tank wall
Tank insulation
Instrument well wall
Instrument well air space
Fire Pan
Fuel/water pool
Insulation
Concrete base
Gravel
0.20 m
Conduit to instrument bunker
Connection well
0.80 m
0.80 m
1.20 m
1.46 m
1.70m
0.40 m
0.60 m

Instrument and Connection Well		
Drawn By: Craig Daviso Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-IW-IW-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 26/06/06	Scale: 1:25

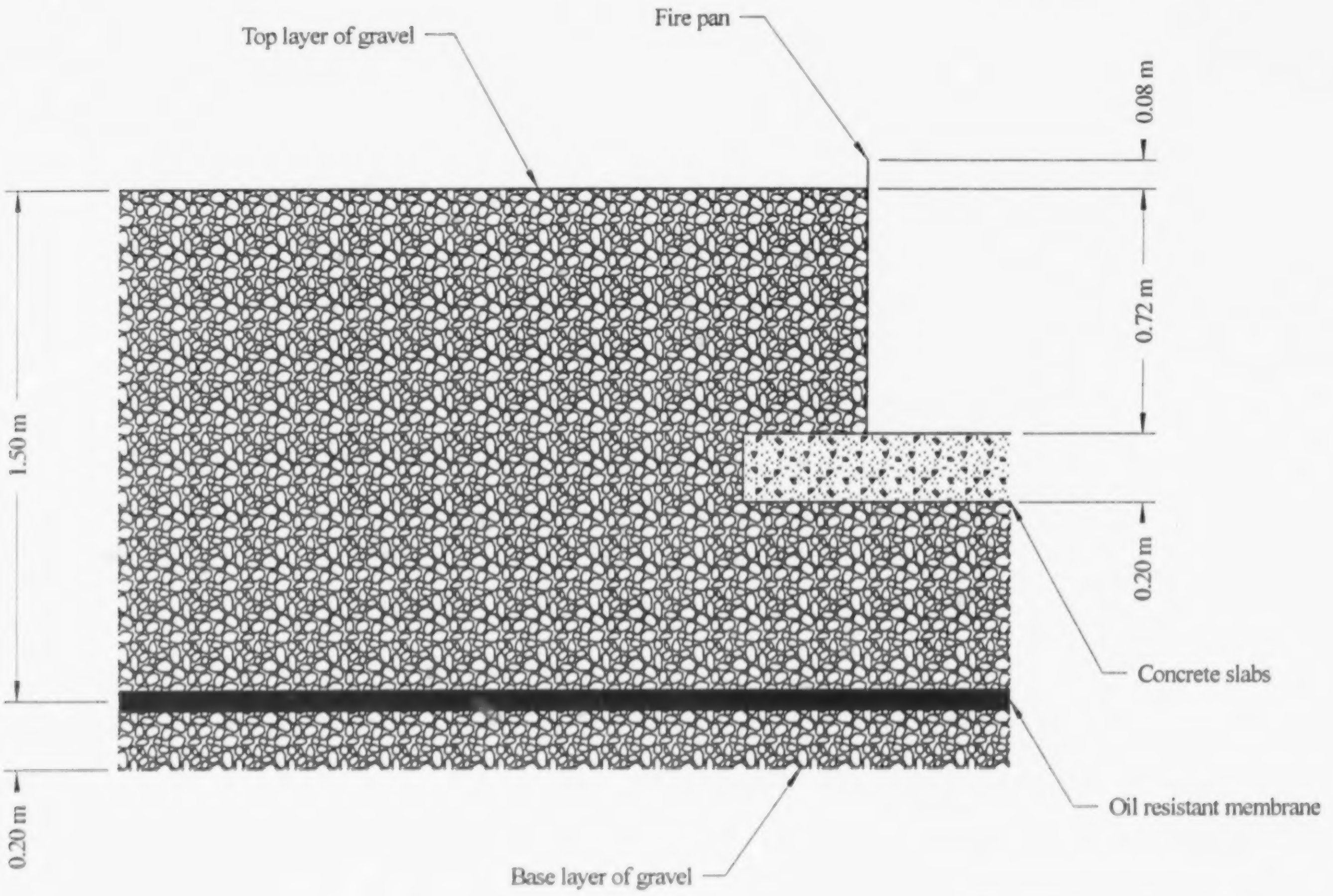

Pipe to instrument well (steel)
Conduit inlet for DFTs from middle of fire pan
Conduit inlet from upwind half of fire pan
Connection and access box
PVC conduit to instrument bunker
Conduit inlet for middle calorimeter and fire thermocouples

Fire Pan and Railcar Instrumentation and Control Cable Access Box

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-IW-AB-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 26/06/06	Scale: 1:20

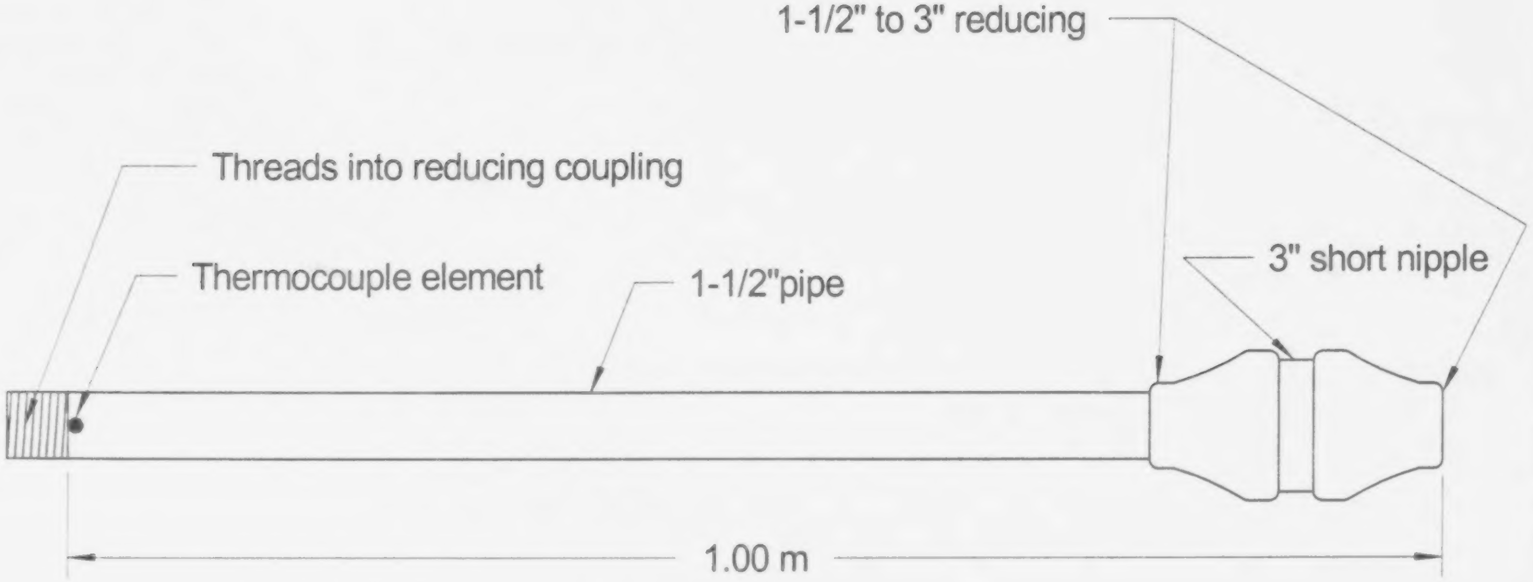

Fuel/water pool
Vapour vent
Packing to act as a vapour barrier
Plastic pipe to prevent conduction
Connection box
Common conduit to main connection and access box

DFT Cable Exit from Fire Pan		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-IW-DE-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 12/09/06	Scale: 1:20

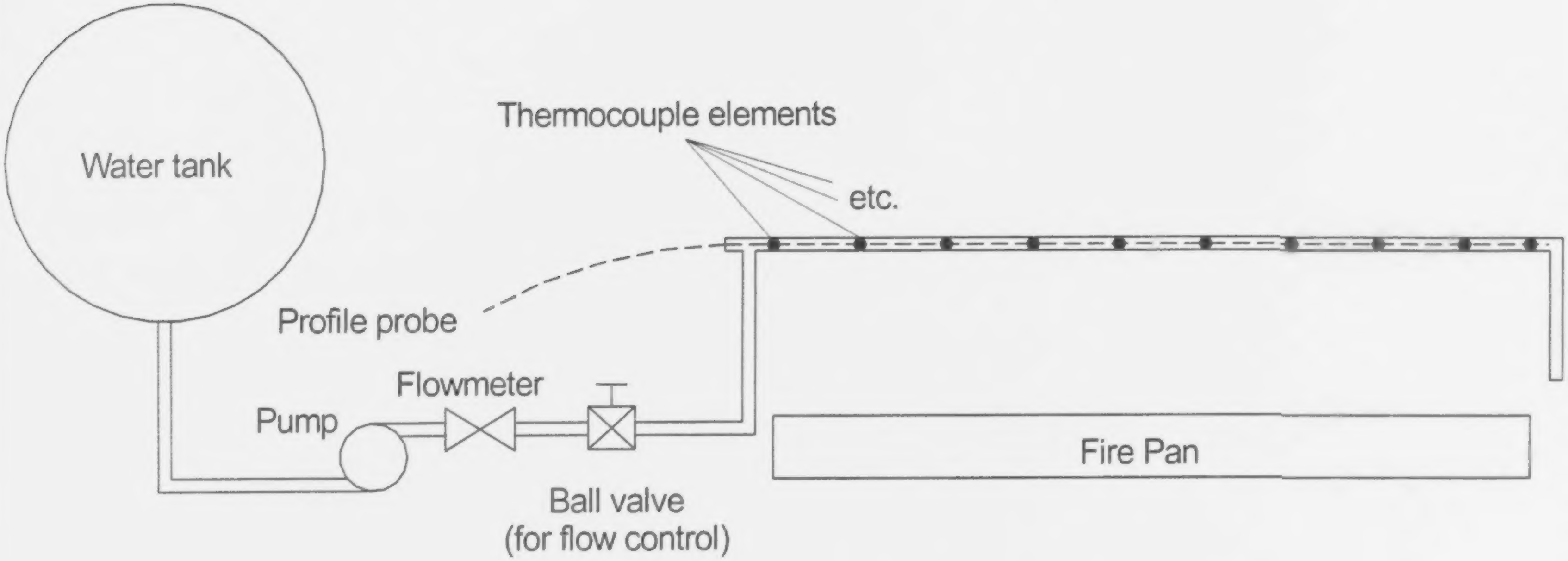

Top layer of gravel
Fire pan
0.08 m
0.72 m
1.50 m
0.20 m
Concrete slabs
0.20 m
Oil resistant membrane
Base layer of gravel

Ground Preparation for Fire Pan

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-IW-GP-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 26/06/06	Scale: 1:20


1-1/2" to 3" reducing
Threads into reducing coupling
3" short nipple
Thermocouple element
1-1/2"pipe
1.00 m

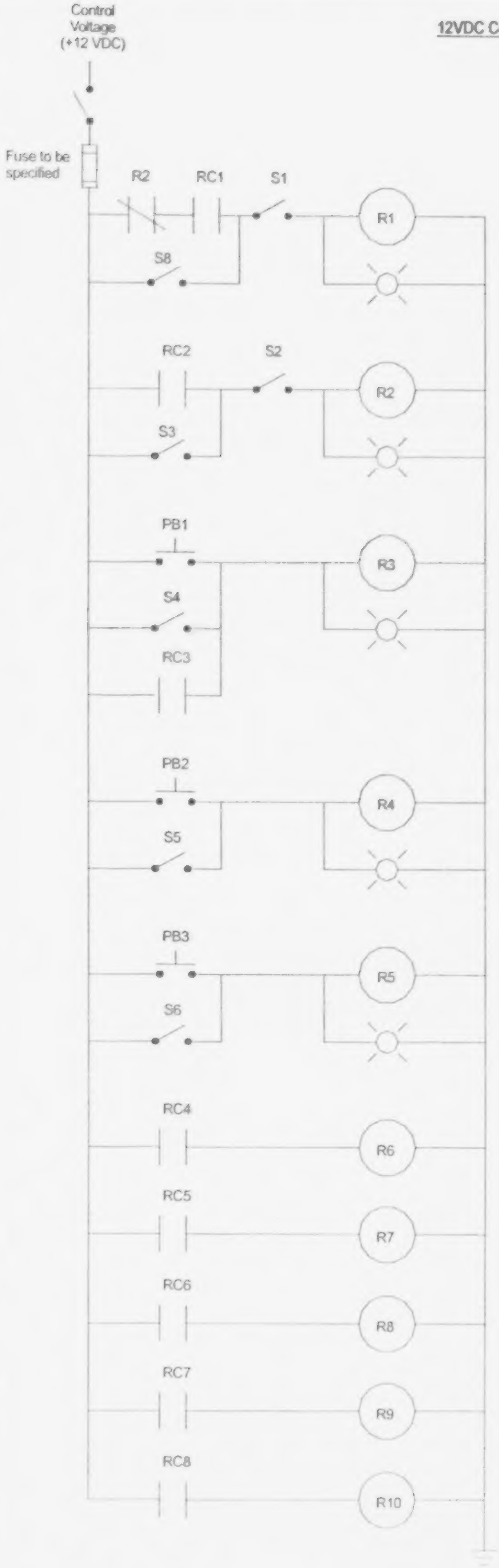
Calorimeter Section		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-CL-CS-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 30/06/06	Scale: 1:5


Water tank
Thermocouple elements
etc.
Profile probe
Flowmeter
Pump
Ball valve
(for flow control)
Fire Pan

Calorimeter Schematic

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-CL-CC-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 30/06/06	Scale: N.T.S.

12VDC Control Circuit

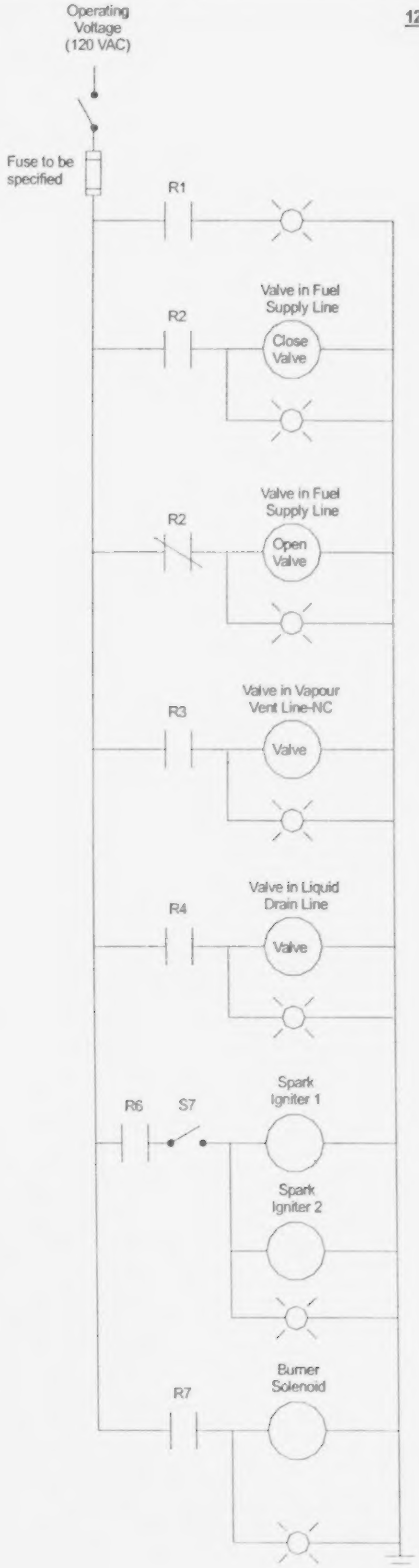

Control Voltage (+12 VDC)
Fuse to be specified
R2
RC1
S1
R1
S8
RC2
S2
R2
S3
PB1
R3
S4
RC3
PB2
R4
S5
PB3
R5
S6
RC4
R6
RC5
R7
RC6
R8
RC7
R9
RC8
R10

S - designates manual switch in control bunker
PB1 & 2 - designate manual pushbuttons in instrument bunker for testing
PB3 - designates manual pushbutton in control bunker
RC - desigantes relay controlled by computer DAC system
Indicator lights are in control bunker
Relays are in instrument bunker

Wiring Diagram for Robust Test Control

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-RC-RC-01	
	Vs.: 1	Sheet: 1 of 3
	Date: 30/06/06	Scale: N.T.S.

120VAC Control Circuit


Operating Voltage (120 VAC)
Fuse to be specified
R1
Valve in Fuel Supply Line
R2
Close Valve
Valve in Fuel Supply Line
R2
Open Valve
Valve in Vapour Vent Line-NC
R3
Valve
Valve in Liquid Drain Line
R4
Valve
R6
S7
Spark Igniter 1
Spark Igniter 2
Burner Solenoid
R7

Controls in instrument bunker except for R1 and S7
R1 is near fuel pump
S7 is in field in sight of burners
120V cables should be shielded

Wiring Diagram for Robust Test Control

Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

Dwg. No.: RT-RC-RC-01

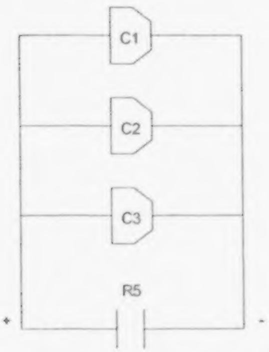
Vs.: 1

Sheet: 2 of 3

Date: 30/06/06

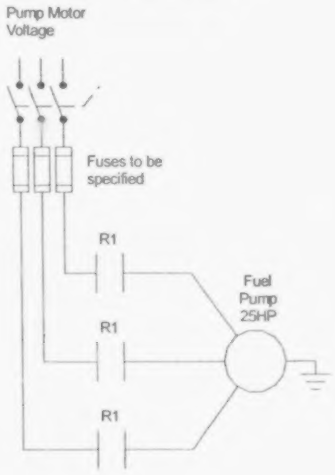
Scale: N.T.S.

SLR Camera Control



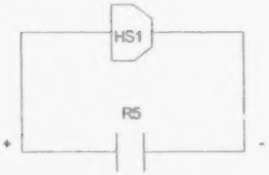
C denotes still cameras in remote locations
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Cameras 4 & 5 are wired directly to the control bunker

Fuel Pump Power Circuit


Pump Motor Voltage
Fuses to be specified
R1
R1
R1
Fuel Pump 25HP

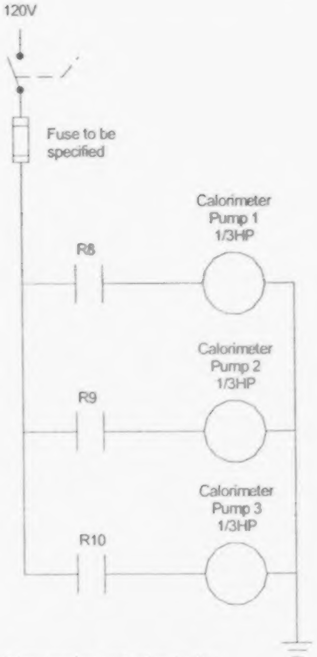
Note: High power cables should not be routed inside instrument bunker
Motor requires overload protection

High Speed Camera Control



HS denotes high speed camera
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Need to verify that camera returns to capture mode after activation otherwise will require seperate circuit

Calorimeter Pump Power Circuit

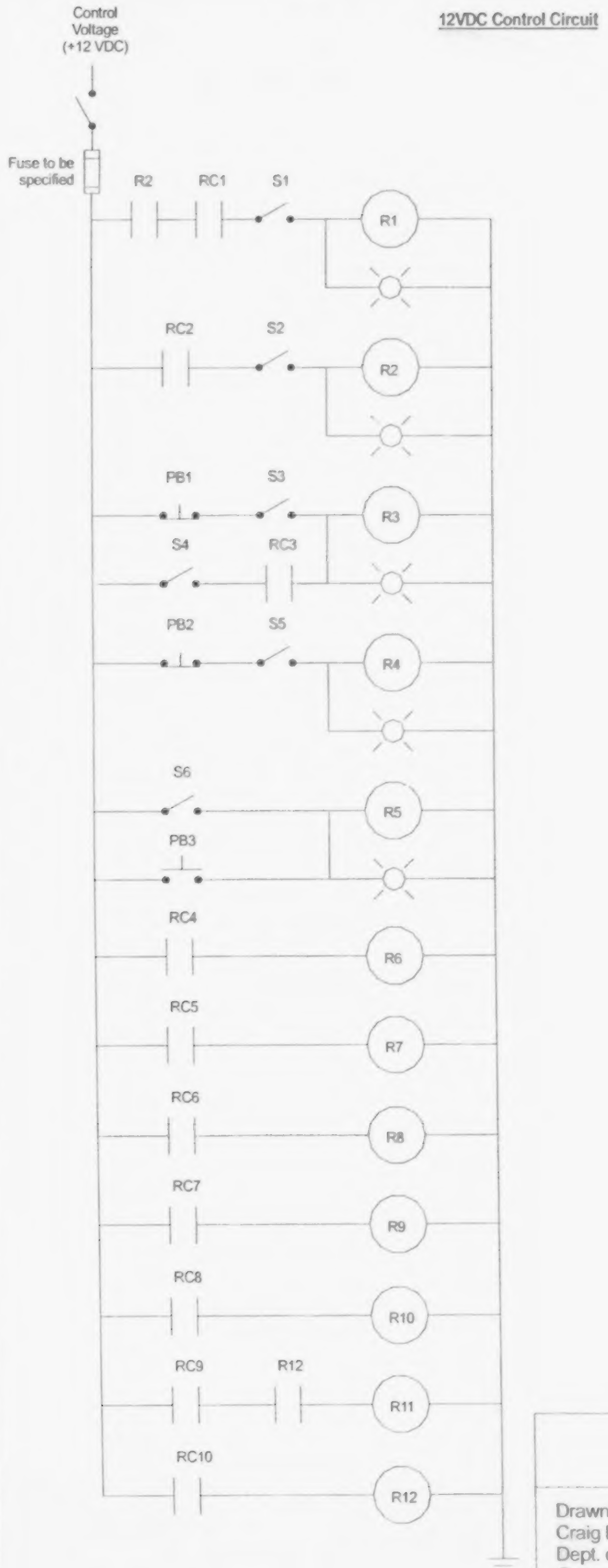

120V
Fuse to be specified
Calorimeter Pump 1 1/3HP
R8
Calorimeter Pump 2 1/3HP
R9
Calorimeter Pump 3 1/3HP
R10

Note: Motors require overload protection

Wiring Diagram for Robust Test Control

Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

Dwg. No.: RT-RC-RC-01
Vs.: 1
Sheet: 3 of 3
Date: 30/06/06
Scale: N.T.S.

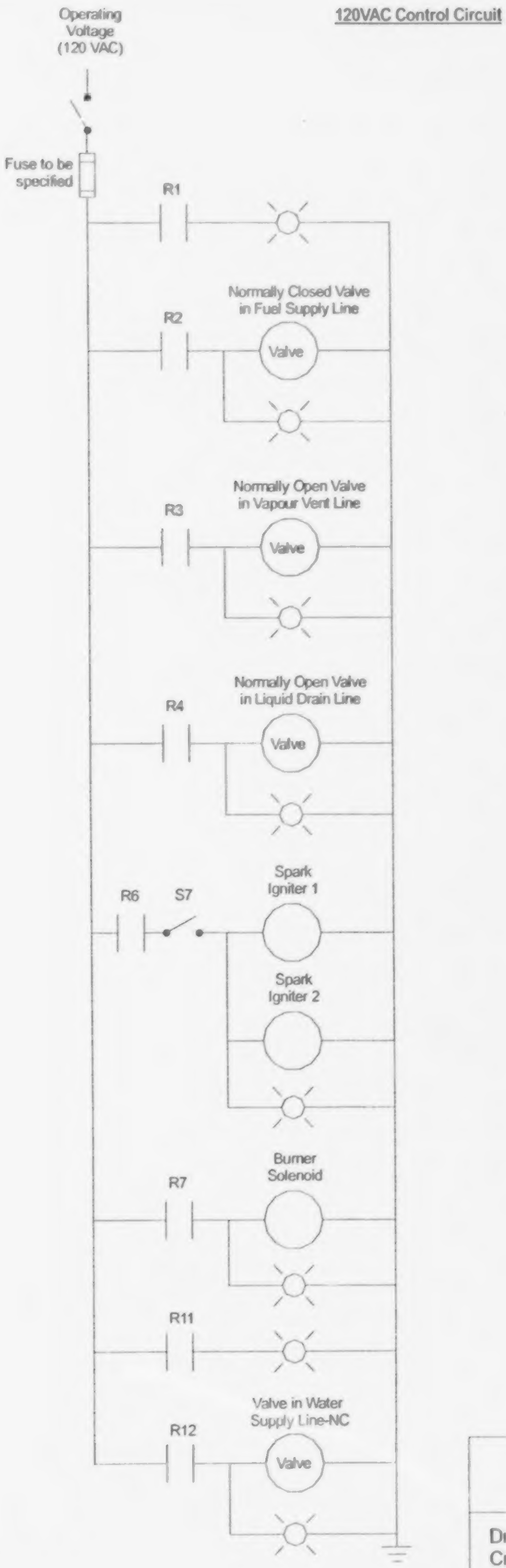

12VDC Control Circuit
Control Voltage (+12 VDC)
Fuse to be specified
R2
RC1
S1
R1
RC2
S2
R2
PB1
S3
R3
S4
RC3
PB2
S5
R4
S6
R5
PB3
RC4
R6
RC5
R7
RC6
R8
RC7
R9
RC8
R10
RC9
R12
R11
RC10
R12

S - designates manual switch in personel bunker
PB1 & 2 - designate manual pushbuttons in instrument bunker for testing
PB3 - designates manual pushbutton in control bunker
RC - desigantes relay controlled by computer DAC system
Indicator lights are in control bunker
Relays are in instrument bunker except R1, R8, R9, R10, R11 which are in field near pumps

Wiring Diagram for
Safe Test Control

Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

Dwg. No.: RT-SC-SC-01
Vs.: 1
Sheet: 1 of 3
Date: 22/08/06
Scale: N.T.S.

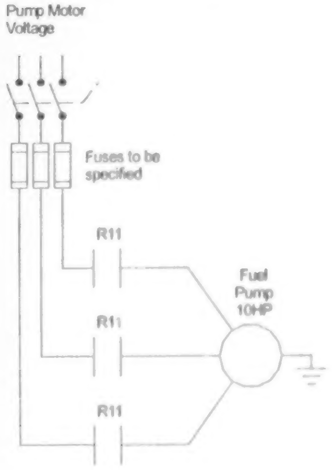

120VAC Control Circuit
Operating Voltage (120 VAC)
Fuse to be specified
R1
R2
Normally Closed Valve in Fuel Supply Line
Valve
R3
Normally Open Valve in Vapour Vent Line
Valve
R4
Normally Open Valve in Liquid Drain Line
Valve
R6
S7
Spark Igniter 1
Spark Igniter 2
R7
Burner Solenoid
R11
R12
Valve in Water Supply Line-NC
Valve

Controls in instrument bunker except for
R1, R11 and S6
R1 and R11are near fuel and water pumps
S7 is in field in sight of propane burners
120V cables should be shielded

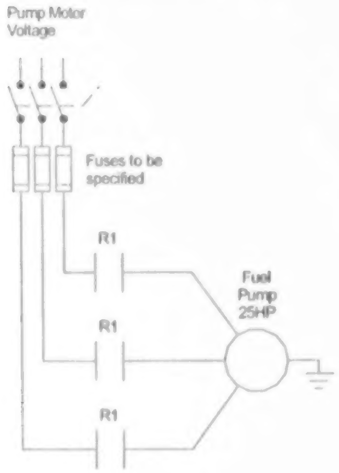
Wiring Diagram for Safe Test Control

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-SC-SC-01	
	Vs.: 1	Sheet: 2 of 3
	Date: 22/08/06	Scale: N.T.S.

Water Pump Power Circuit

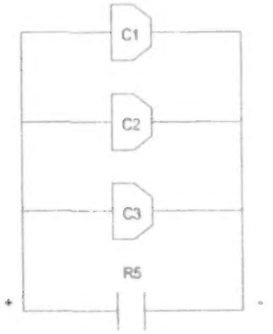

Pump Motor
Voltage
Fuses to be
specified
R11
R11
R11
Fuel
Pump
10HP

Fuel Pump Power Circuit


Pump Motor
Voltage
Fuses to be
specified
R1
R1
R1
Fuel
Pump
25HP

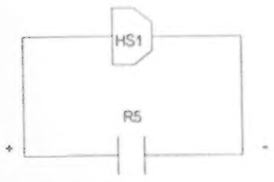
Note: High power cables should not be
routed inside instrument bunker
Motor requires overload protection

SLR Camera Control



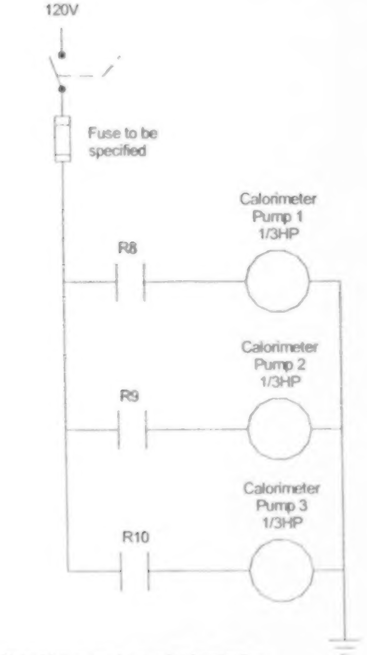
C denotes still cameras in remote locations
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Cameras 4 & 5 are wired directly to the control bunker

High Speed Camera Control



HS denotes high speed camera
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Need to verify that camera returns to capture mode after activation otherwise will require seperate circuit

Calorimeter Pump Power Circuit

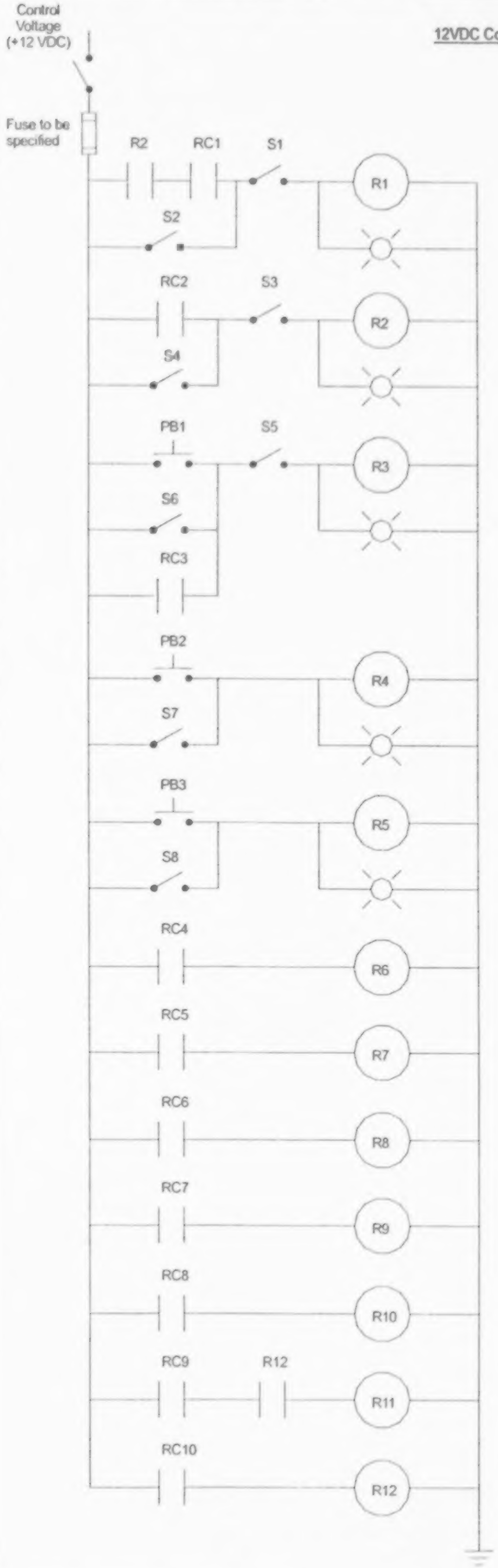

120V
Fuse to be
specified
Calorimeter
Pump 1
1/3HP
R8
Calorimeter
Pump 2
1/3HP
R9
Calorimeter
Pump 3
1/3HP
R10

Note: Motors require overload protection

Wiring Diagram for
Safe Test Control

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-SC-SC-01	
	Vs.: 1	Sheet: 3 of 3
	Date: 22/08/06	Scale: N.T.S.

12VDC Control Circuit


Control
Voltage
(+12 VDC)
Fuse to be
specified
R2
RC1
S1
R1
S2
RC2
S3
R2
S4
PB1
S5
R3
S6
RC3
PB2
R4
S7
PB3
R5
S8
RC4
R6
RC5
R7
RC6
R8
RC7
R9
RC8
R10
RC9
R12
R11
RC10
R12

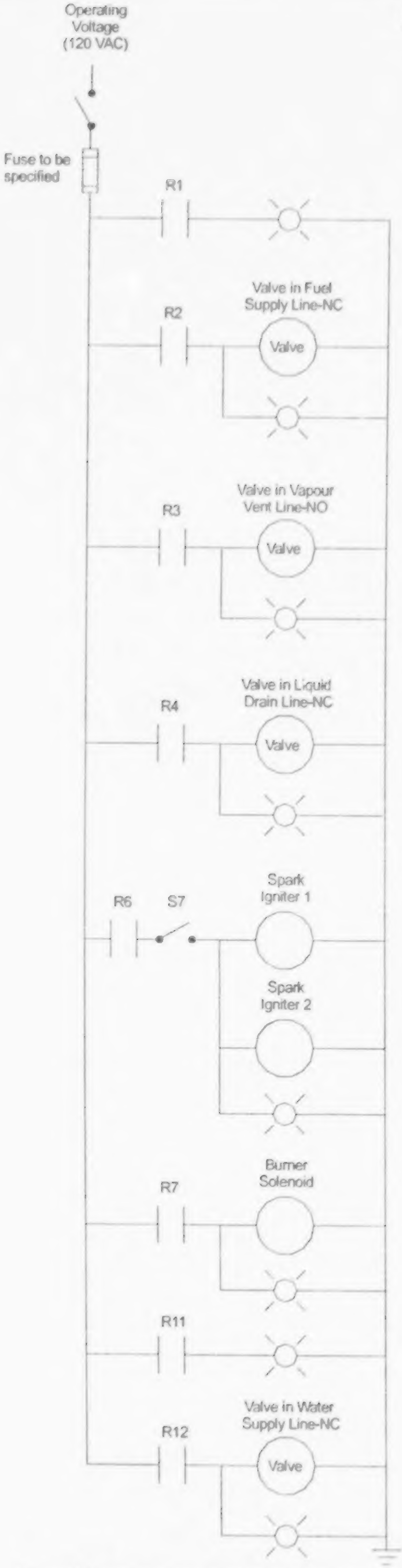
S - designates manual switch in personel bunker
PB1 & 2 - designate manual pushbuttons in instrument bunker for testing
PB3 - designates manual pushbutton in control bunker
RC - desigantes relay controlled by computer DAC system
Indicator lights are in control bunker
Relays are in instrument bunker except R1, R8, R9, R10, R11 which are in field near pumps

Wiring Diagram for Test Control

Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

Dwg. No.: RT-CT-BC-01
Vs.: 1
Sheet: 1 of 3
Date: 22/08/06
Scale: N.T.S.

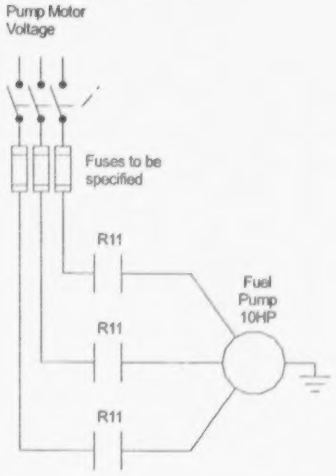
120VAC Control Circuit


Operating Voltage (120 VAC)
Fuse to be specified
R1
R2
Valve in Fuel Supply Line-NC
Valve
R3
Valve in Vapour Vent Line-NO
Valve
R4
Valve in Liquid Drain Line-NC
Valve
R6
S7
Spark Igniter 1
Spark Igniter 2
R7
Burner Solenoid
R11
R12
Valve in Water Supply Line-NC
Valve

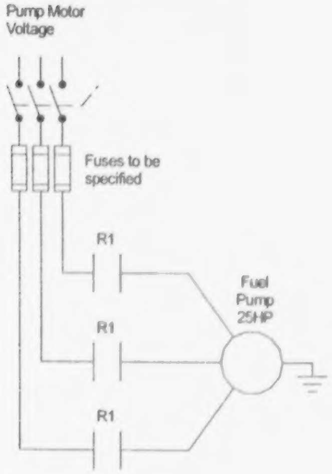
Controls in instrument bunker except for R1, R11 and S7
R1 and R11 are near fuel and water pumps
S7 is in field in sight of burners
120V cables should be shielded

Wiring Diagram for Test Control		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-CT-BC-01	
	Vs.: 1	Sheet: 2 of 3
	Date: 22/08/06	Scale: N.T.S.

Water Pump Power Circuit

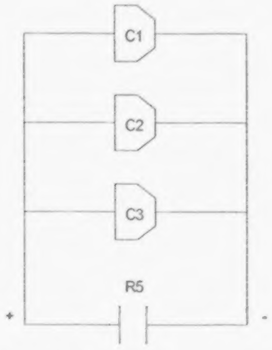

Pump Motor Voltage
Fuses to be specified
R11
Fuel Pump 10HP
R11
R11

Fuel Pump Power Circuit


Pump Motor Voltage
Fuses to be specified
R1
Fuel Pump 25HP
R1
R1

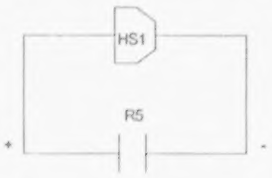
Note: High power cables should not be routed inside instrument bunker
Motors requires overload protection

SLR Camera Control



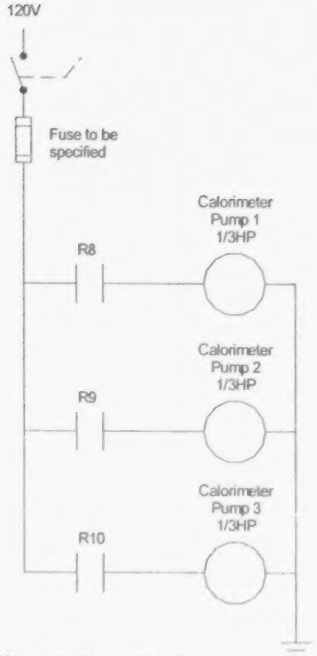
C denotes still cameras in remote locations
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Cameras 4 & 5 are wired directly to the control bunker

High Speed Camera Control



HS denotes high speed camera
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Need to verify that camera returns to capture mode after activation otherwise will require seperate circuit

Calorimeter Pump Power Circuit

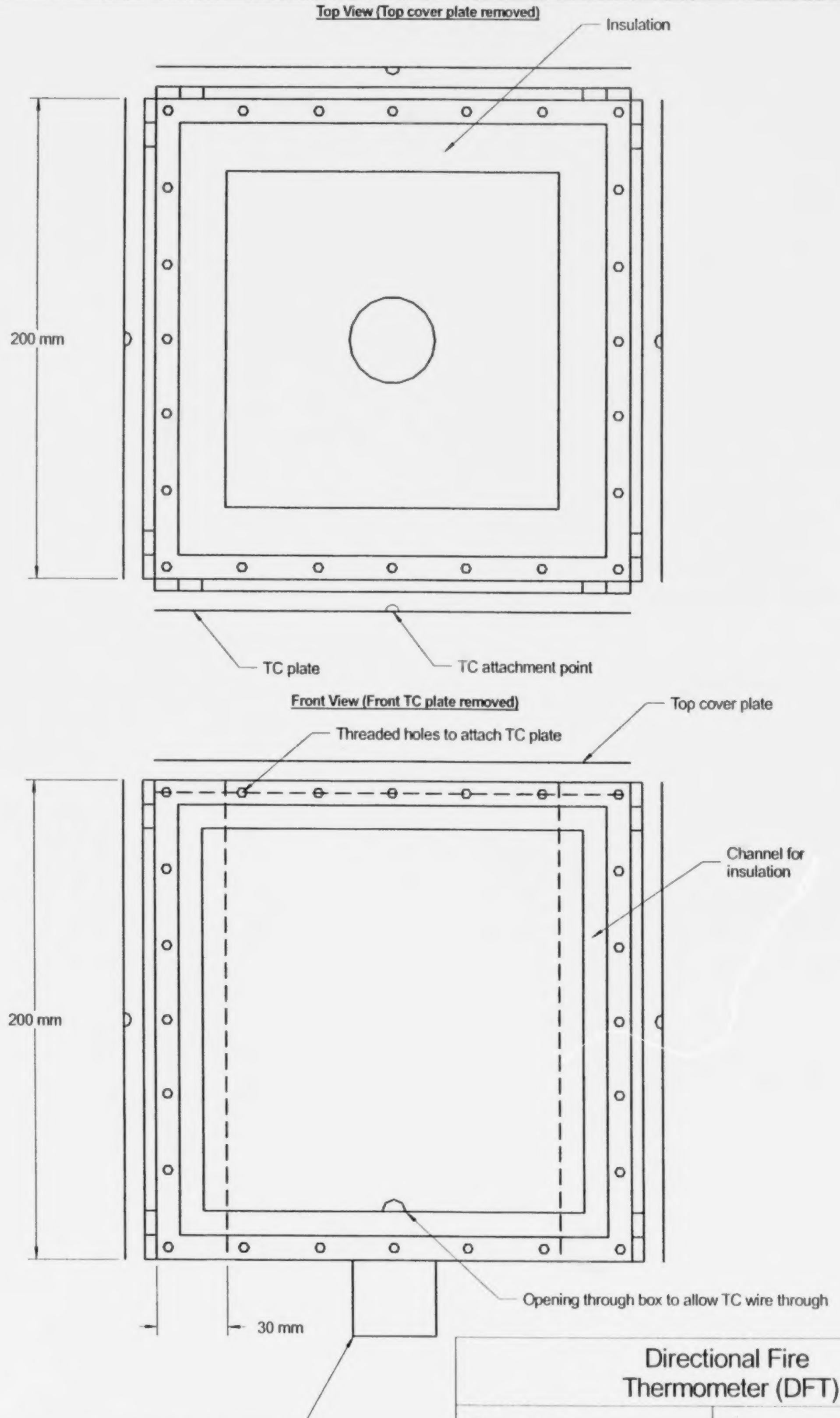

120V
Fuse to be specified
Calorimeter Pump 1 1/3HP
R8
Calorimeter Pump 2 1/3HP
R9
Calorimeter Pump 3 1/3HP
R10

Note: Motors require overload protection

Wiring Diagram for Test Control

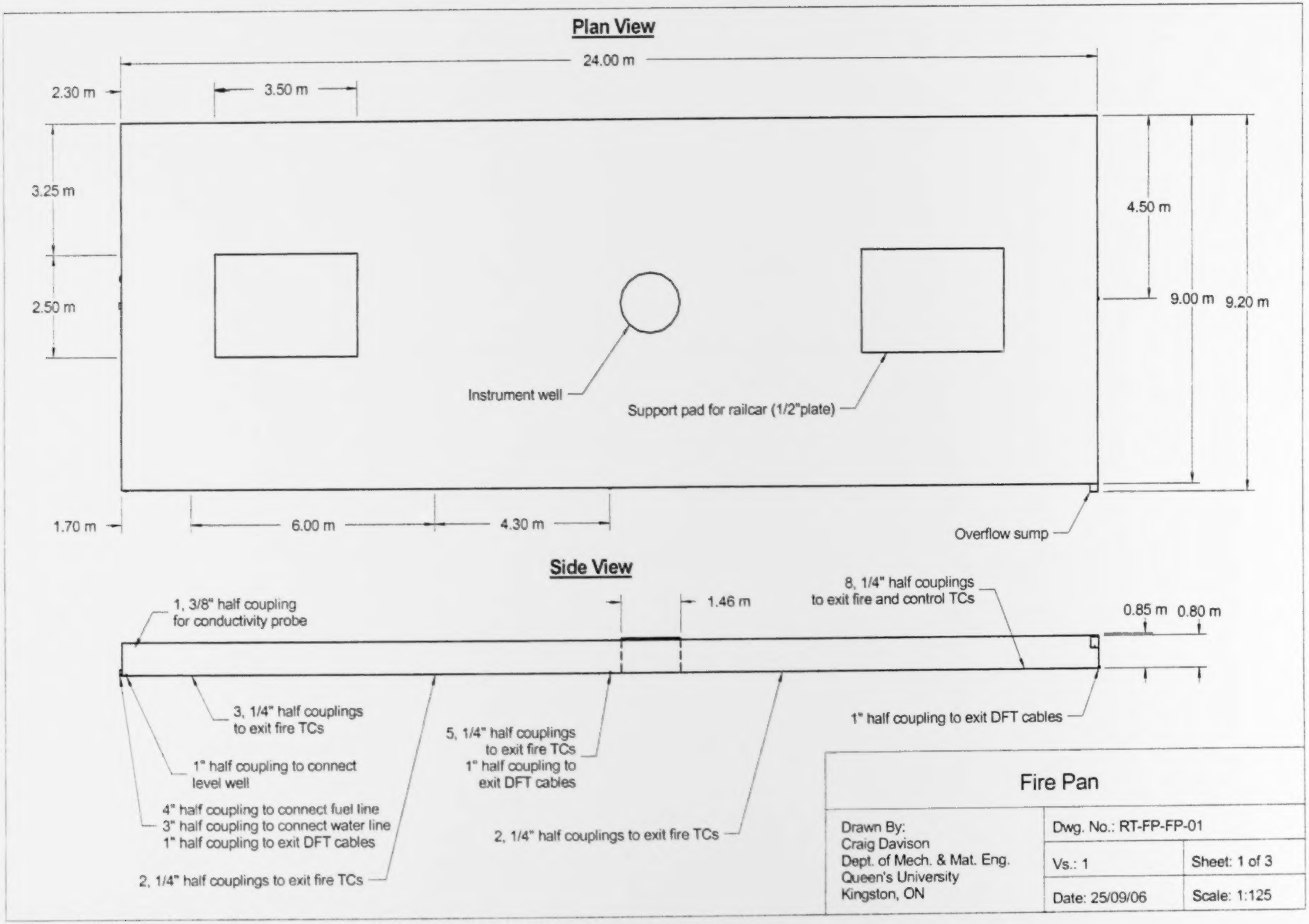
Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

Dwg. No.: RT-CT-BC-01
Vs.: 1
Sheet: 3 of 3
Date: 22/08/06
Scale: N.T.S.

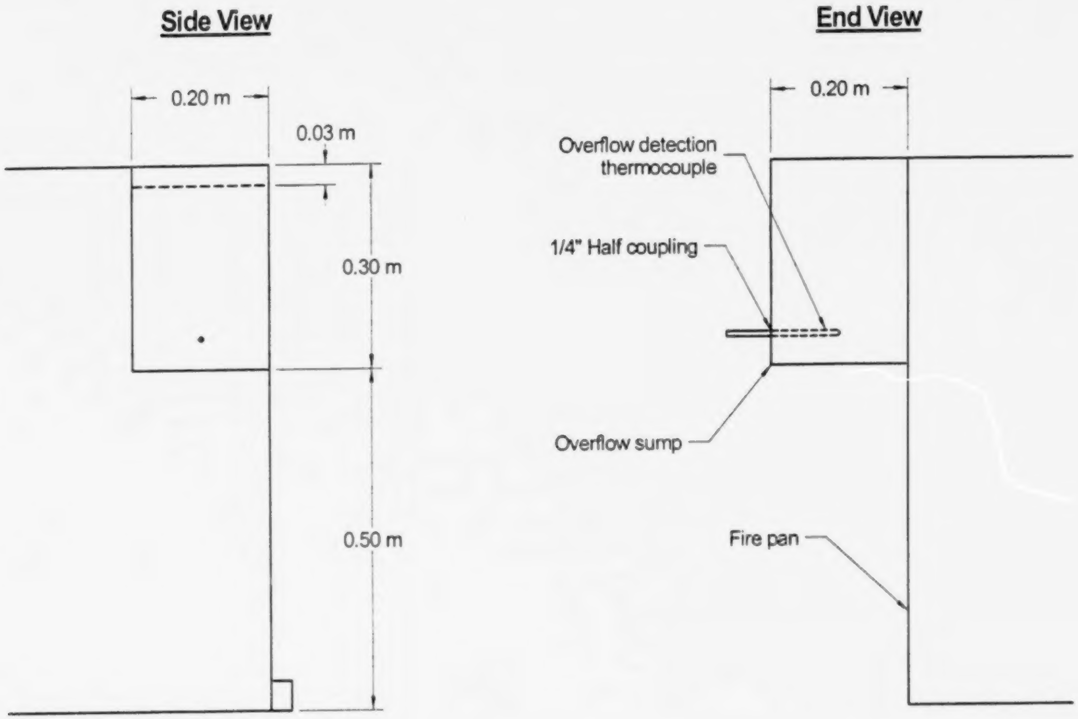

Top View (Top cover plate removed)
Insulation
200 mm
TC plate
TC attachment point
Front View (Front TC plate removed)
Top cover plate
Threaded holes to attach TC plate
Channel for insulation
200 mm
Opening through box to allow TC wire through
30 mm
1" NPT coupling for routing TC wires

Directional Fire
Thermometer (DFT)

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-DF-DF-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 30/06/06	Scale: 1:2.5

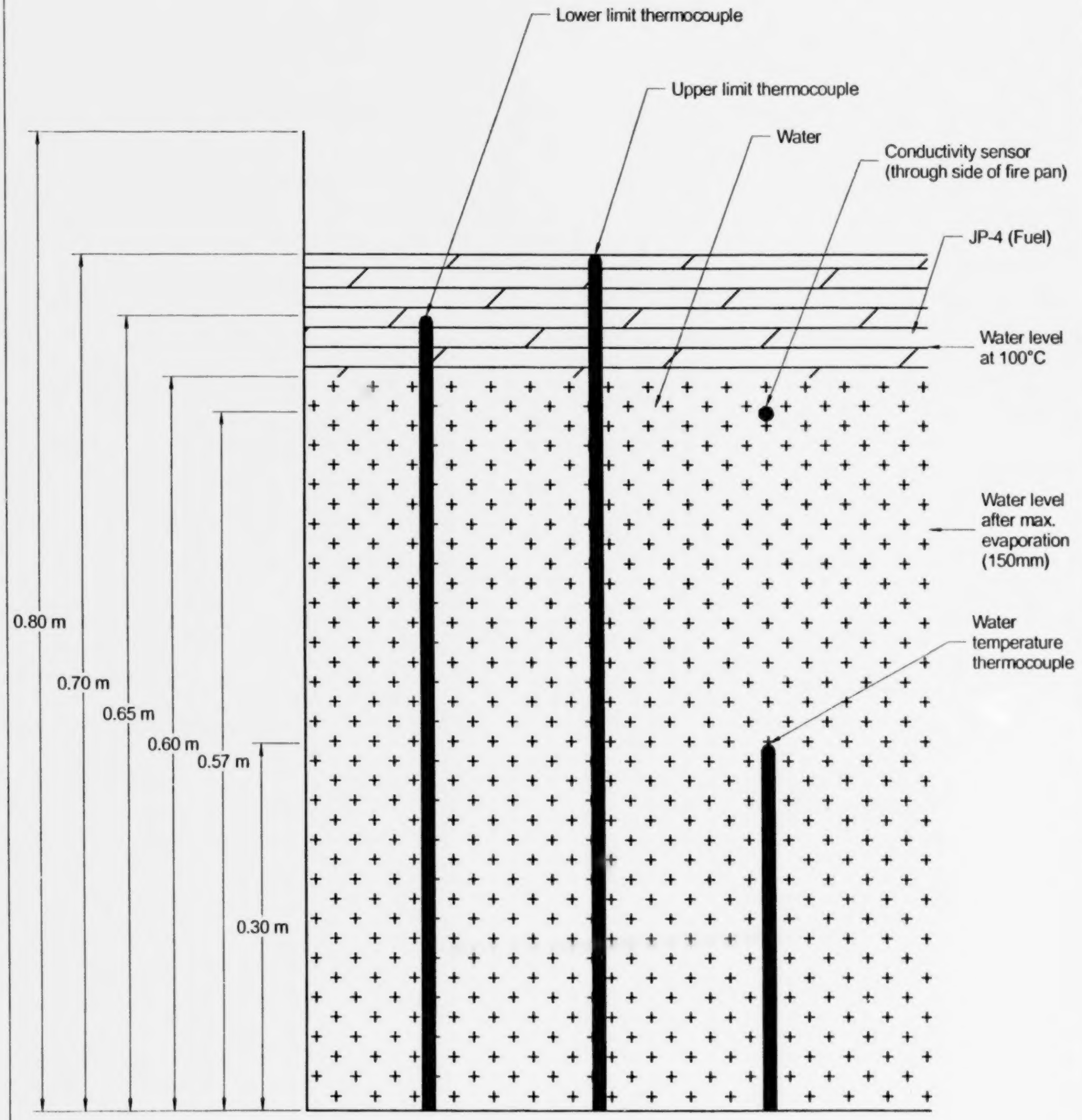

Plan View
24.00 m
2.30 m
3.50 m
3.25 m
2.50 m
4.50 m
9.00 m
9.20 m
Instrument well
Support pad for railcar (1/2"plate)
1.70 m
6.00 m
4.30 m
Overflow sump
Side View
1, 3/8" half coupling
for conductivity probe
1.46 m
8, 1/4" half couplings
to exit fire and control TCs
0.85 m
0.80 m
3, 1/4" half couplings
to exit fire TCs
1" half coupling to connect
level well
4" half coupling to connect fuel line
3" half coupling to connect water line
1" half coupling to exit DFT cables
2, 1/4" half couplings to exit fire TCs
5, 1/4" half couplings
to exit fire TCs
1" half coupling to
exit DFT cables
2, 1/4" half couplings to exit fire TCs
1" half coupling to exit DFT cables
Fire Pan
Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON
Dwg. No.: RT-FP-FP-01
Vs.: 1
Sheet: 1 of 3
Date: 25/09/06
Scale: 1:125

Detail of Overflow Sump

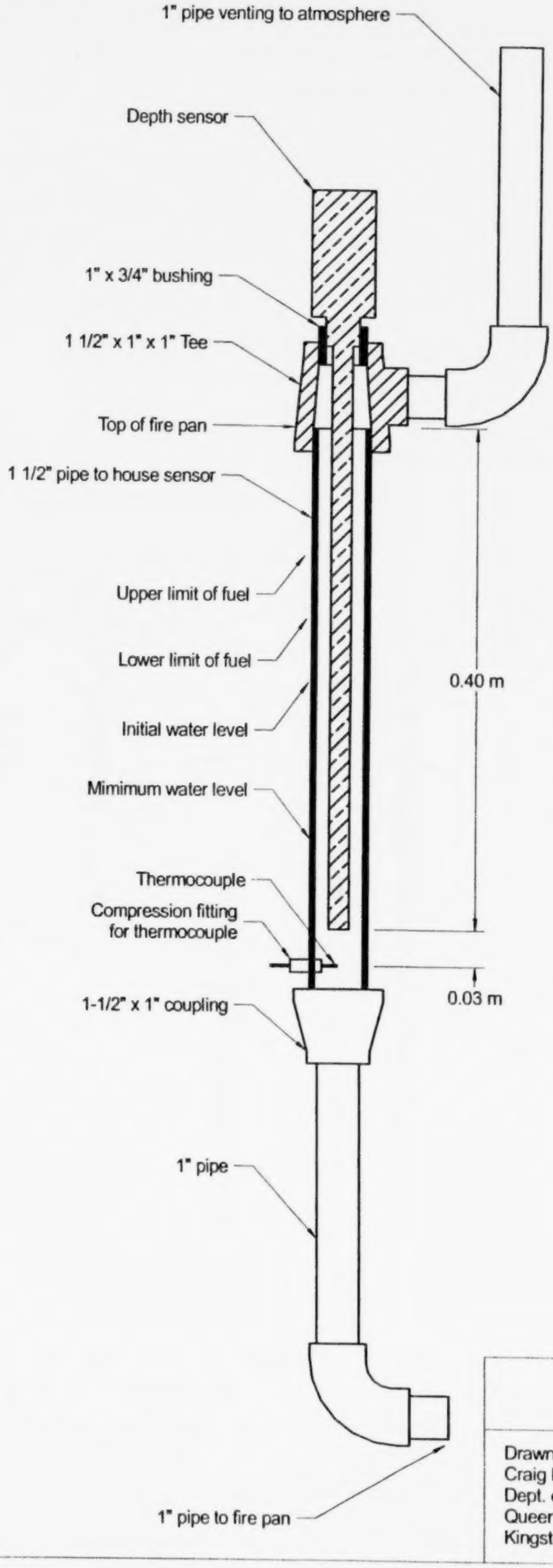

Side View
0.20 m
0.03 m
0.30 m
0.50 m
End View
0.20 m
Overflow detection thermocouple
1/4" Half coupling
Overflow sump
Fire pan

Fire Pan		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-FP-FP-01	
	Vs.: 1	Sheet: 2 of 3
	Date: 4/07/06	Scale: 1:10

Elevation of Fire Pan Showing Liquid and Sensor Heights


Lower limit thermocouple
Upper limit thermocouple
Water
Conductivity sensor (through side of fire pan)
JP-4 (Fuel)
Water level at 100°C
Water level after max. evaporation (150mm)
Water temperature thermocouple
0.80 m
0.70 m
0.65 m
0.60 m
0.57 m
0.30 m

Fire Pan		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-FP-FP-01	
	Vs.: 1	Sheet: 3 of 3
	Date: 21/08/06	Scale: 1:5


1" pipe venting to atmosphere
Depth sensor
1" x 3/4" bushing
1 1/2" x 1" x 1" Tee
Top of fire pan
1 1/2" pipe to house sensor
Upper limit of fuel
Lower limit of fuel
0.40 m
Initial water level
Mimimum water level
Thermocouple
Compression fitting
for thermocouple
0.03 m
1-1/2" x 1" coupling
1" pipe
1" pipe to fire pan

Note:
Depth sensor requires a minimum 30cm earth covering to shield from thermal radiation

Cross section only used to show position of depth sensor

Level Well

Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

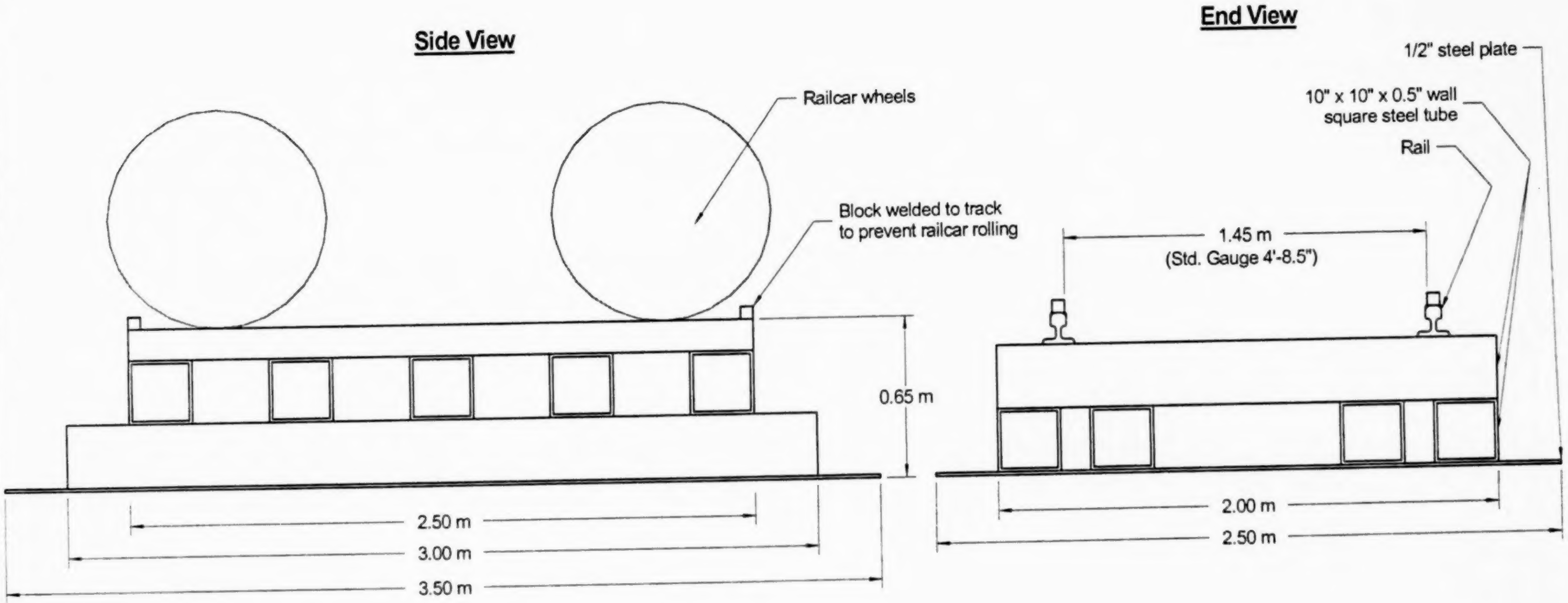
Dwg. No.: RT-FP-LW-01

Vs.: 1

Sheet: 1 of 1

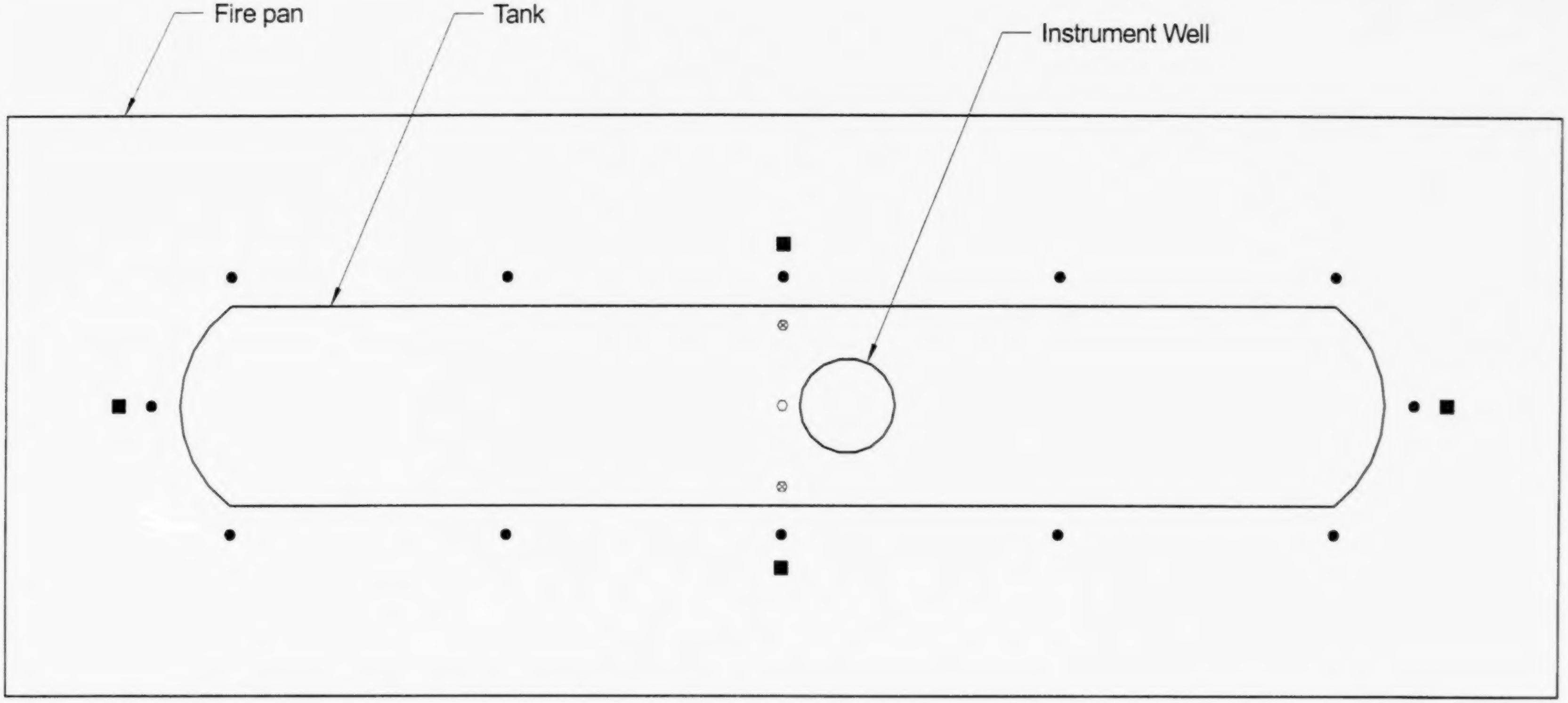
Date: 05/07/06

Scale: 1:5


Side View
Railcar wheels
Block welded to track to prevent railcar rolling
0.65 m
2.50 m
3.00 m
3.50 m
End View
1/2" steel plate
10" x 10" x 0.5" wall square steel tube
Rail
1.45 m
(Std. Gauge 4'-8.5")
2.00 m
2.50 m

Railcar Support

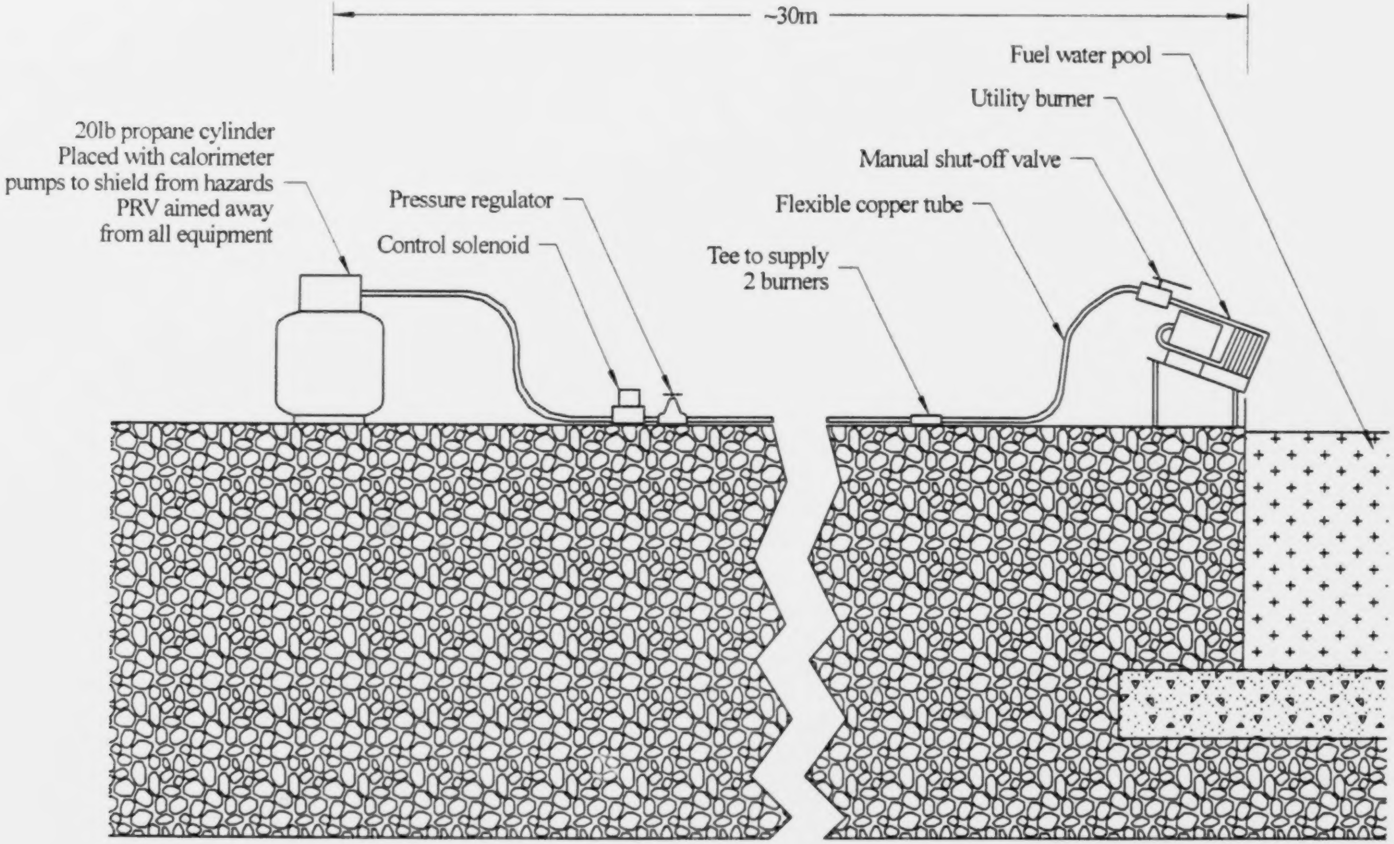
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-FP-RS-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 5/07/06	Scale: 1:25



● Fire TC located at elevation aligned with tank midline
○ Fire TC located at elevation over top of tank
⊗ Fire TC located at elevation aligned with tank bottom
■ DFT located at elevation aligned with tank midline

Fire Thermocouple and Directional Fire Thermometer Locations

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-FT-FT-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 5/07/06	Scale: 1:100

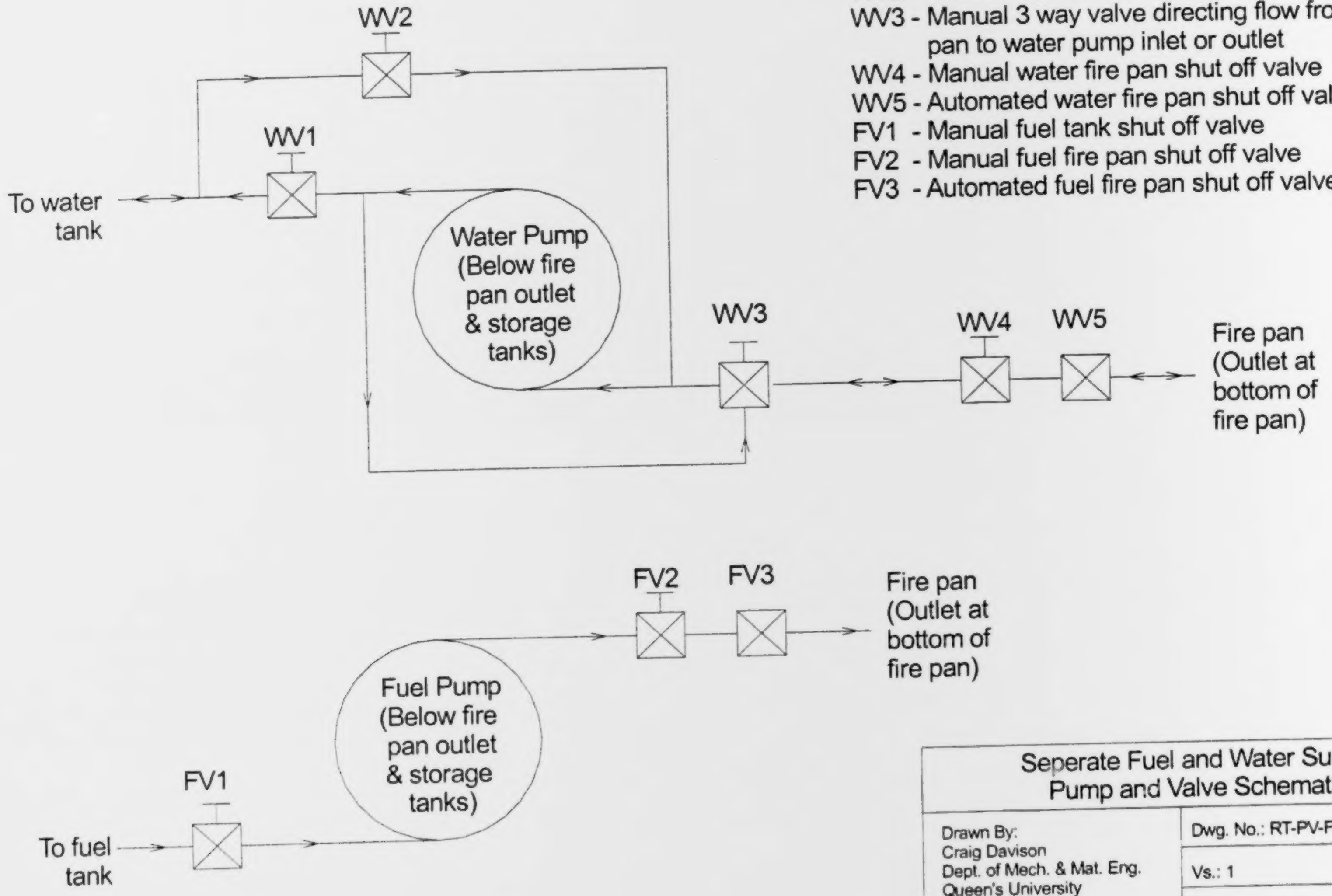

~30m
20lb propane cylinder
Placed with calorimeter
pumps to shield from hazards
PRV aimed away
from all equipment
Pressure regulator
Control solenoid
Tee to supply
2 burners
Flexible copper tube
Manual shut-off valve
Utility burner
Fuel water pool

Note: 2 burners to be installed at upwind end of fire pan
approximately 4.5m apart - 2.25m from sides

Fire Pan
Ignition System

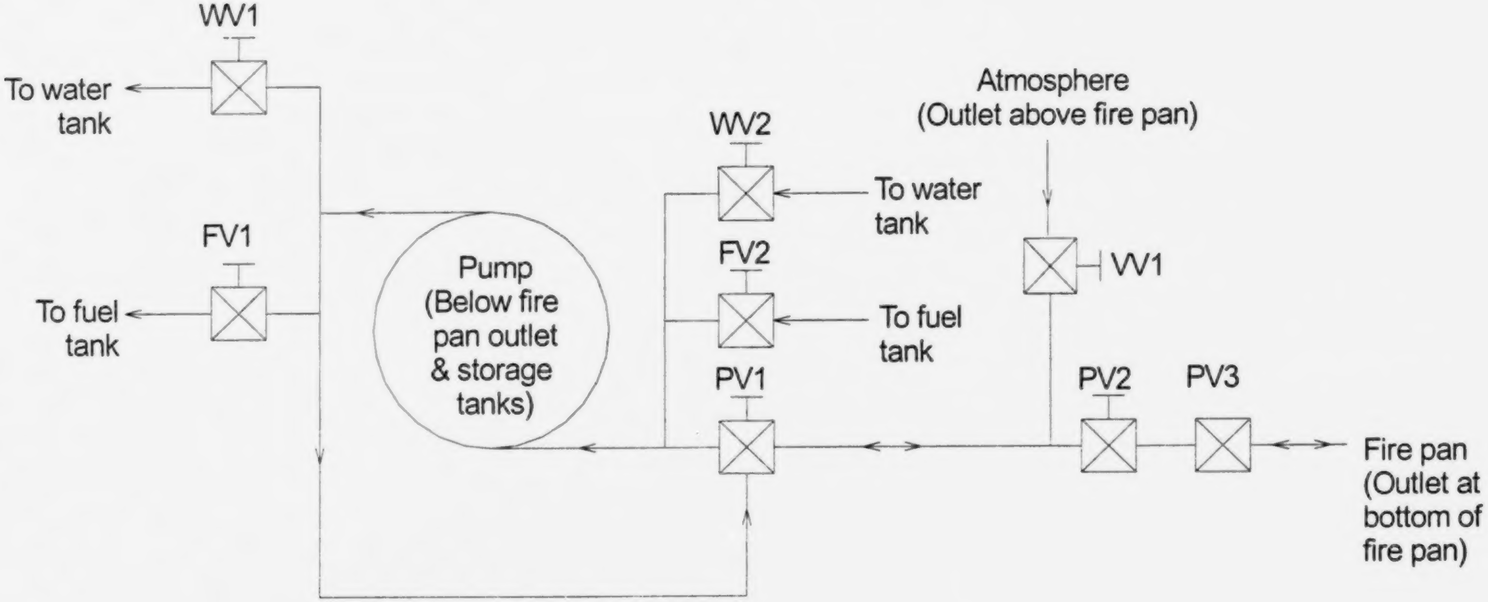
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-IG-IG-02	
	Vs.: 2	Sheet: 1 of 1
	Date: 08/08/06	Scale: 1:20

WV1 - Manual water tank return valve
WV2 - Manual water tank outlet valve
WV3 - Manual 3 way valve directing flow from fire pan to water pump inlet or outlet
WV4 - Manual water fire pan shut off valve
WV5 - Automated water fire pan shut off valve
FV1 - Manual fuel tank shut off valve
FV2 - Manual fuel fire pan shut off valve
FV3 - Automated fuel fire pan shut off valve


WV2
WV1
To water tank
Water Pump (Below fire pan outlet & storage tanks)
WV3
WV4
WV5
Fire pan (Outlet at bottom of fire pan)
FV2
FV3
Fire pan (Outlet at bottom of fire pan)
Fuel Pump (Below fire pan outlet & storage tanks)
FV1
To fuel tank

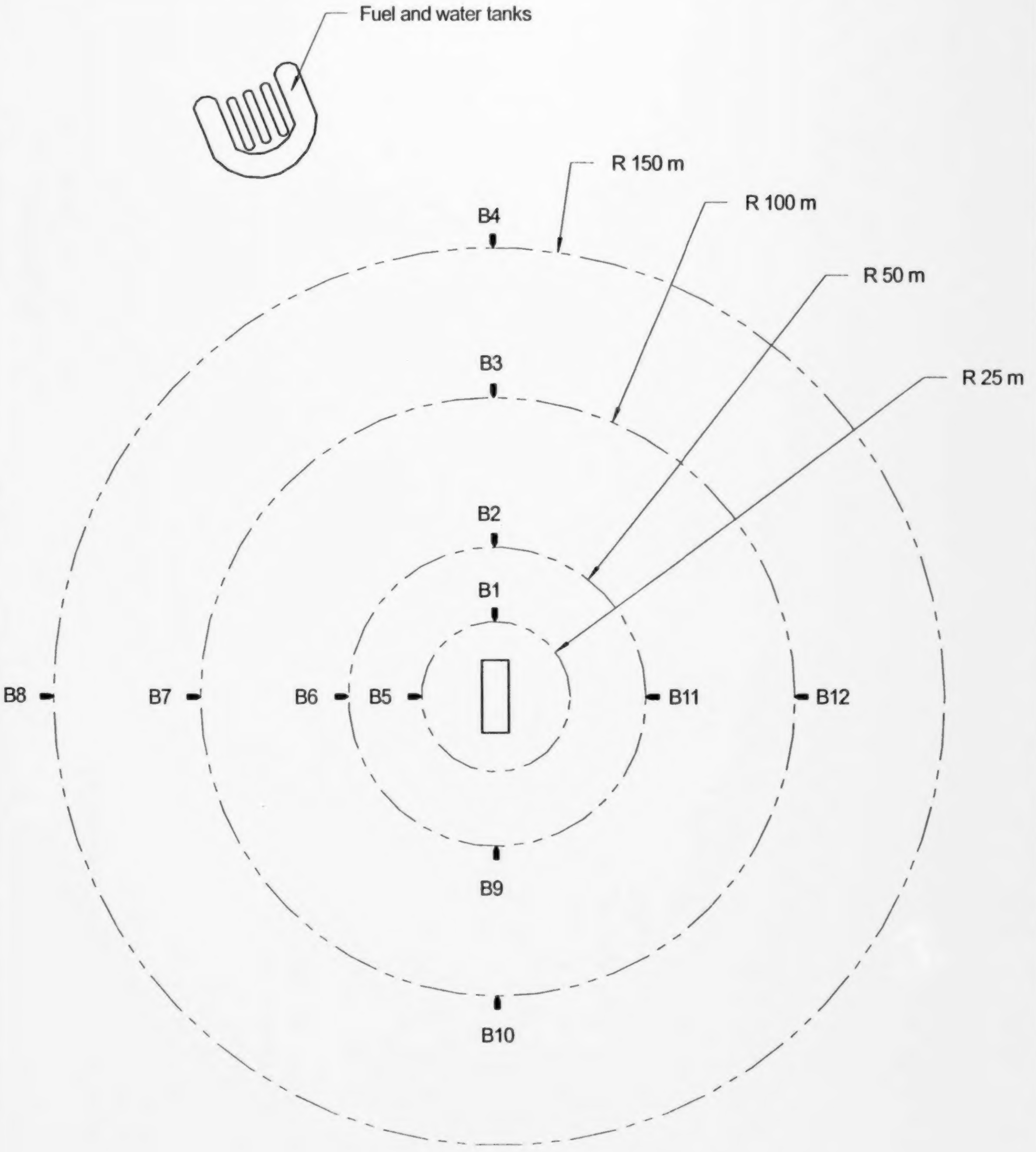
Seperate Fuel and Water Supply Pump and Valve Schematic

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-PV-FW-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 21/08/06	Scale: N.T.S.


WV1
To water tank
FV1
To fuel tank
Pump (Below fire pan outlet & storage tanks)
WV2
To water tank
FV2
To fuel tank
PV1
Atmosphere (Outlet above fire pan)
VV1
PV2
PV3
Fire pan (Outlet at bottom of fire pan)

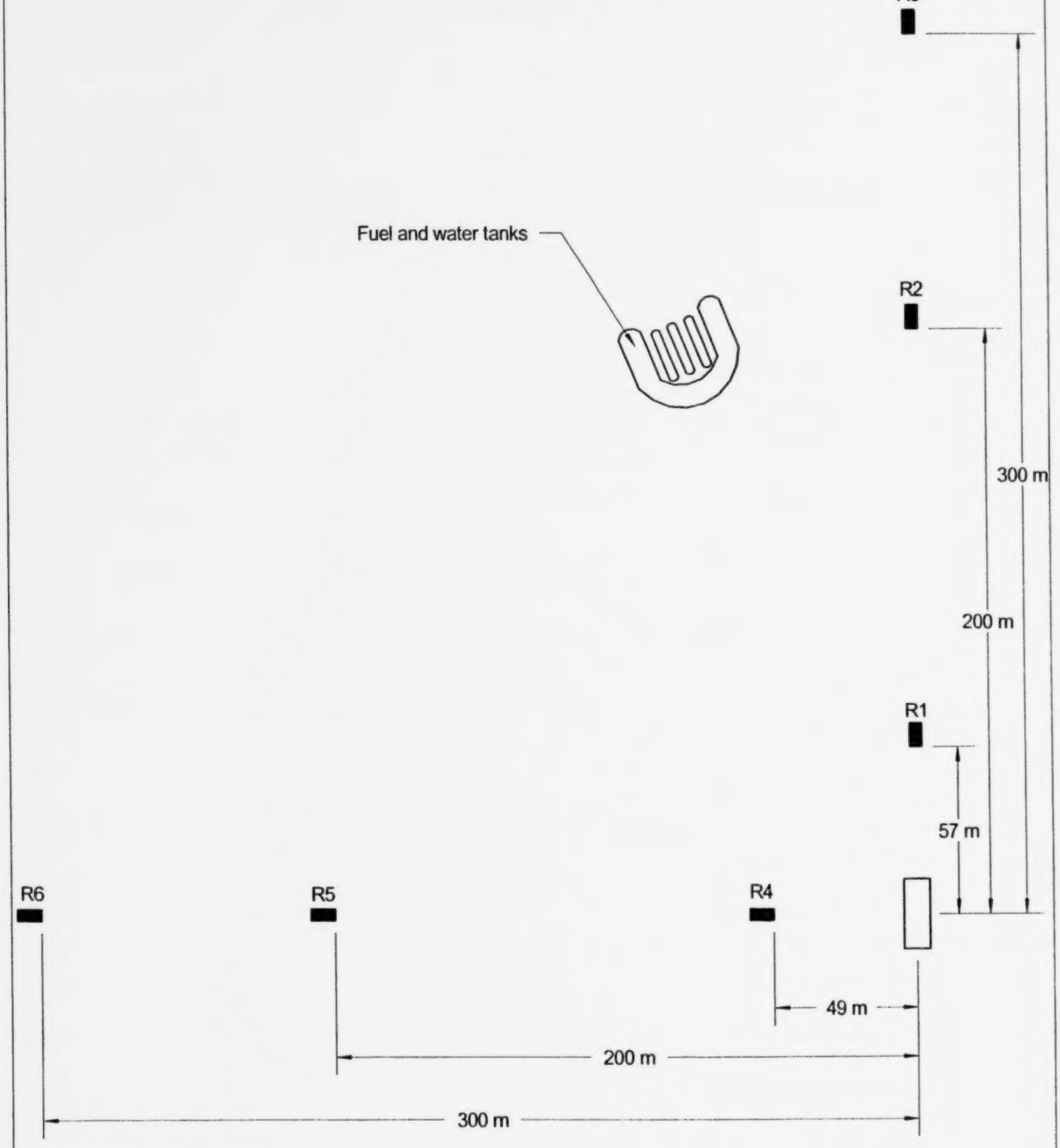
WV1 - Manual water pump outlet valve
WV2 - Manual water pump inlet valve
FV1 - Manual fuel pump outlet valve
FV2 - Manual fuel pump inlet valve
PV1 - Manual 3 way valve directing flow from fire pan to pump inlet or outlet
PV2 - Manual fire pan shut off valve
PV3 - Automated fire pan shut off valve
VV1 - Manual vent valve to allow pumping pipeline dry

Combined Fuel and Water Supply Pump and Valve Schematic		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-PV-PV-01	
	Vs.: 1	Sheet: 1 of 1
	Date:225/08/06	Scale: N.T.S.


Fuel and water tanks
R 150 m
R 100 m
R 50 m
R 25 m
B4
B3
B2
B1
B8
B7
B6
B5
B11
B12
B9
B10

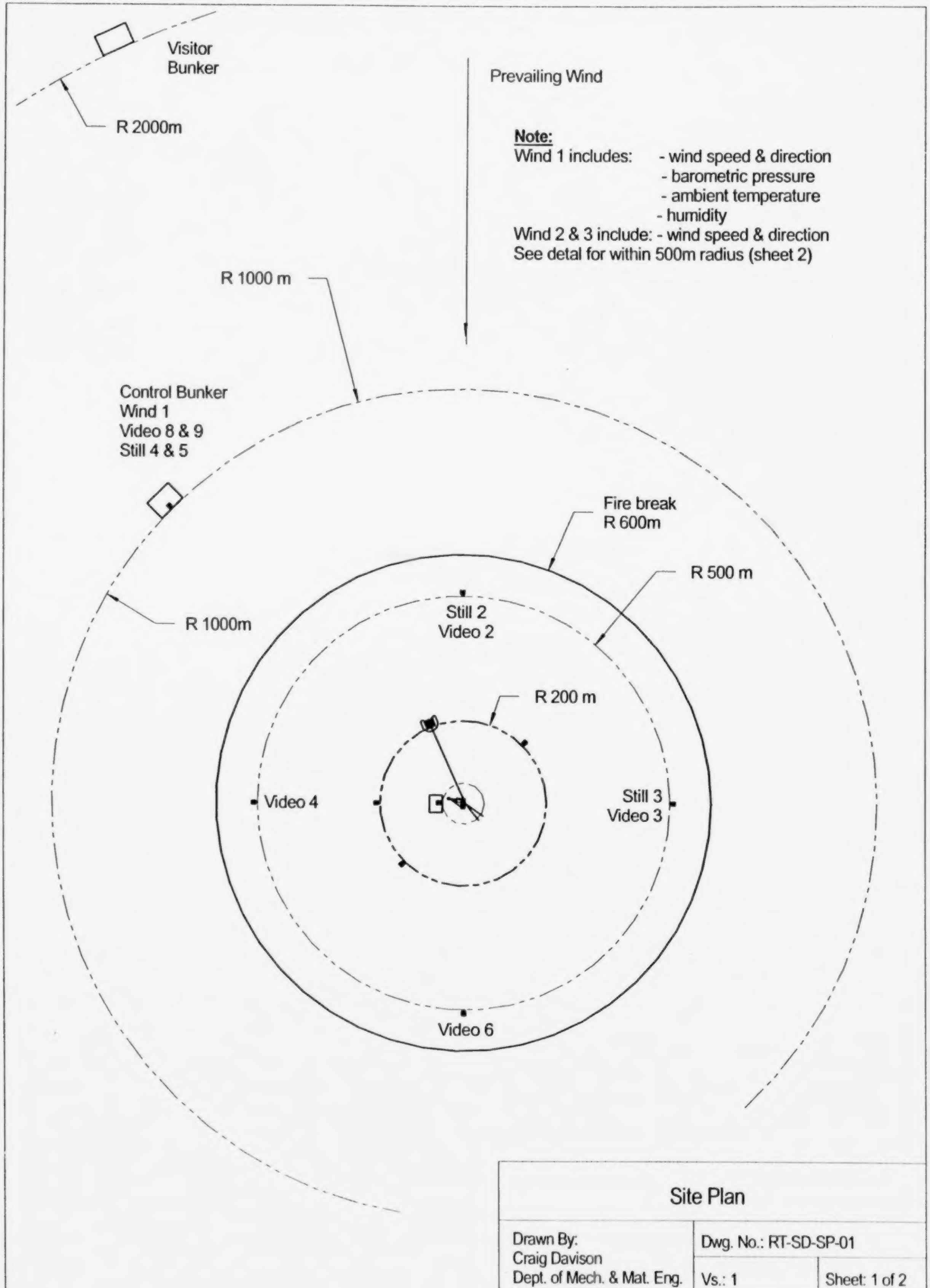
Blast Gauge
Positions

Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-SD-BG-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 06/07/06	Scale: 1:2000


R3
Fuel and water tanks
R2
300 m
200 m
R1
57 m
R6
R5
R4
49 m
200 m
300 m

Radiometer Positions

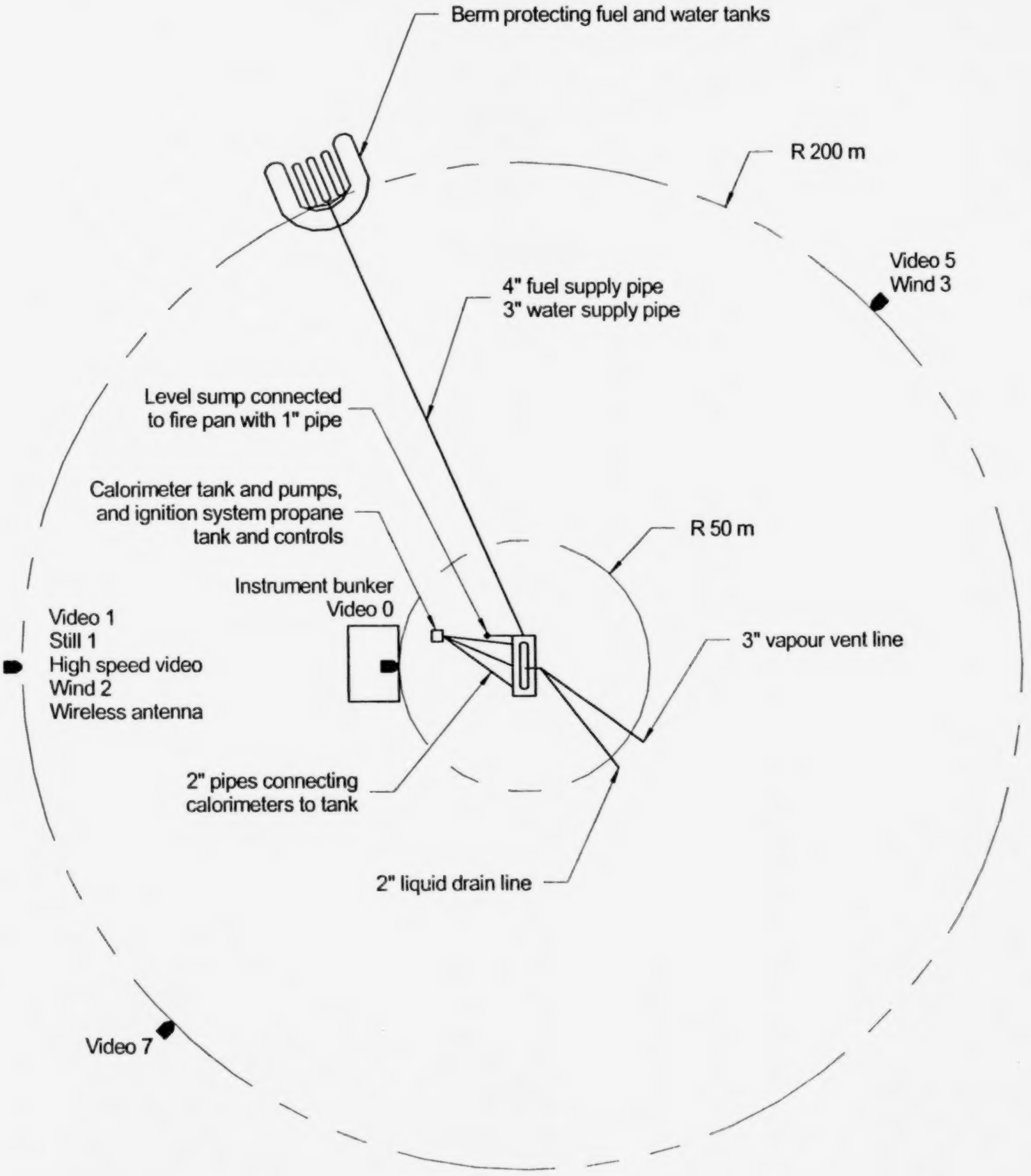
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-SD-RA-01	
	Vs.: 1	Sheet: 1 of 1
	Date: 06/07/06	Scale: 1:2000


Visitor Bunker
R 2000m
Prevailing Wind
R 1000 m
Control Bunker
Wind 1
Video 8 & 9
Still 4 & 5
Fire break
R 600m
R 500 m
R 1000m
Still 2
Video 2
R 200 m
Video 4
Still 3
Video 3
Video 6

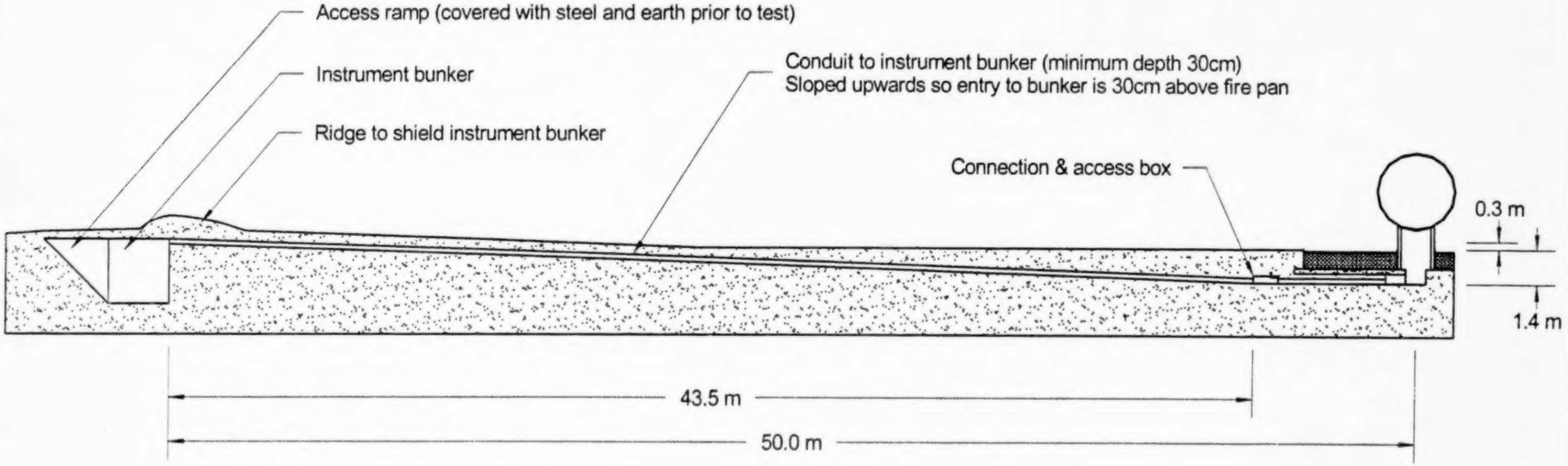
Note:
Wind 1 includes: - wind speed & direction
- barometric pressure
- ambient temperature
- humidity
Wind 2 & 3 include: - wind speed & direction
See detal for within 500m radius (sheet 2)

Site Plan		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-SD-SP-01	
	Vs.: 1	Sheet: 1 of 2
	Date: 07/07/06	Scale: 1:12500

Detail of Site Layout Within 250m Radius


Berm protecting fuel and water tanks
R 200 m
Video 5
Wind 3
4" fuel supply pipe
3" water supply pipe
Level sump connected
to fire pan with 1" pipe
Calorimeter tank and pumps,
and ignition system propane
tank and controls
R 50 m
Instrument bunker
Video 0
Video 1
Still 1
High speed video
Wind 2
Wireless antenna
3" vapour vent line
2" pipes connecting
calorimeters to tank
2" liquid drain line
Video 7

Site Plan		
Drawn By: Craig Davison Dept. of Mech. & Mat. Eng. Queen's University Kingston, ON	Dwg. No.: RT-SD-SP-01	
	Vs.: 1	Sheet: 2 of 2
	Date: 22/08/06	Scale: 1:2500


Access ramp (covered with steel and earth prior to test)
Instrument bunker
Ridge to shield instrument bunker
Conduit to instrument bunker (minimum depth 30cm)
Sloped upwards so entry to bunker is 30cm above fire pan
Connection & access box
0.3 m
1.4 m
43.5 m
50.0 m

Cross Section of Main Instrumentation Conduit		
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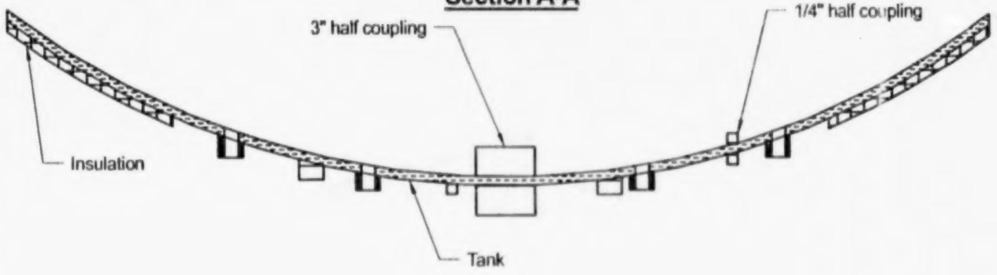
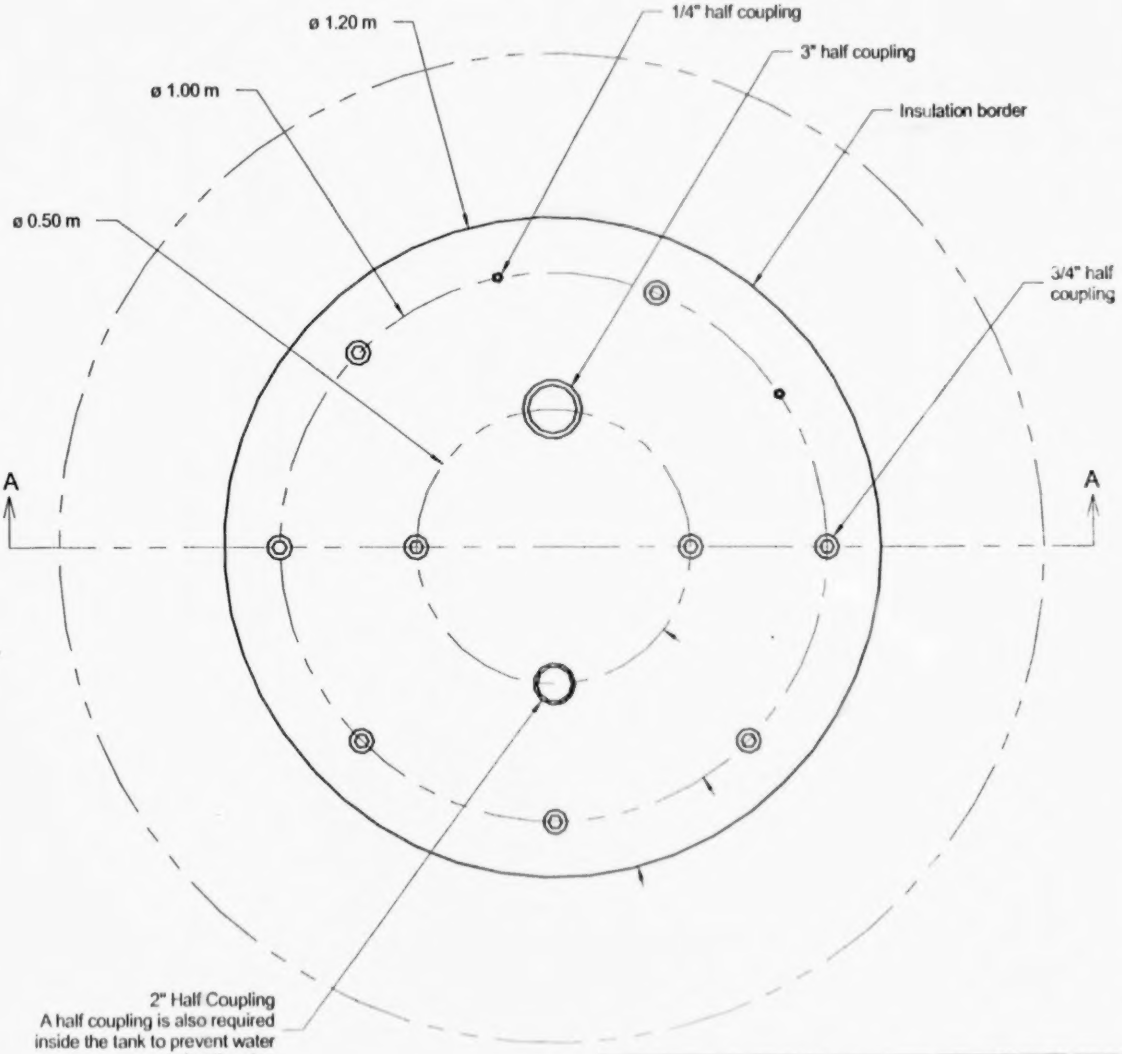
	Vs.: 1	Sheet: 1 of 1
	Date: 07/07/06	Scale: 1:250

Section A-A


3" half coupling
1/4" half coupling
Insulation
Tank

Bottom View


ø 1.20 m
1/4" half coupling
3" half coupling
ø 1.00 m
Insulation border
ø 0.50 m
3/4" half coupling
A
A
2" Half Coupling
A half coupling is also required inside the tank to prevent water entering the pipe

Additional Tank Fittings for Entry Into Instrument Well

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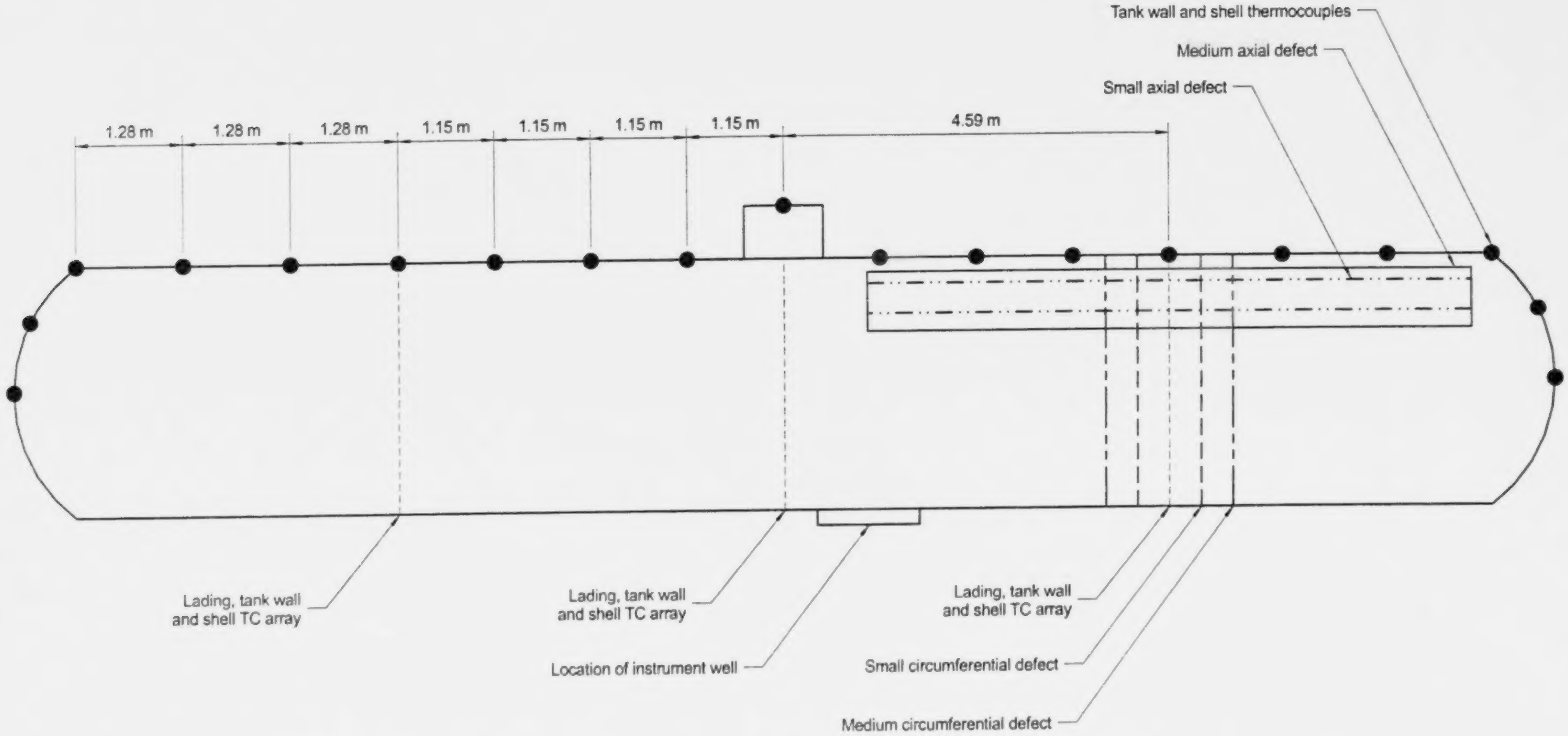
	Vs.: 1	Sheet: 1 of 1
	Date: 10/07/06	Scale: 1:12.5


Tank wall and shell thermocouples
Medium axial defect
Small axial defect
1.28 m
1.28 m
1.28 m
1.15 m
1.15 m
1.15 m
1.15 m
4.59 m
Lading, tank wall and shell TC array
Lading, tank wall and shell TC array
Lading, tank wall and shell TC array
Location of instrument well
Small circumferential defect
Medium circumferential defect

Railcar Tank Wall and Shell Thermocouple Locations

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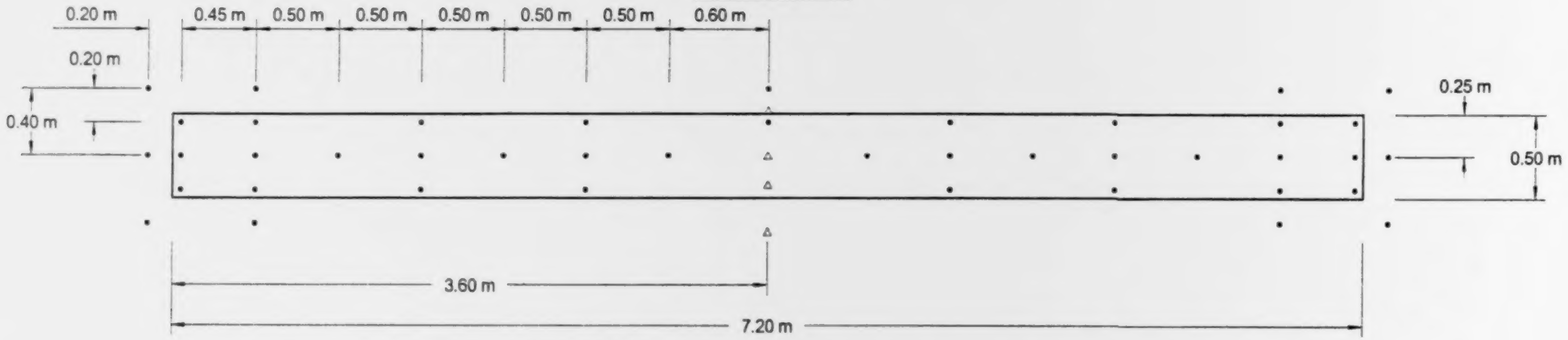
Queen's University
Kingston, ON

Dwg. No.: RT-TT-WS-01

Vs.: 1
Sheet: 1 of 1

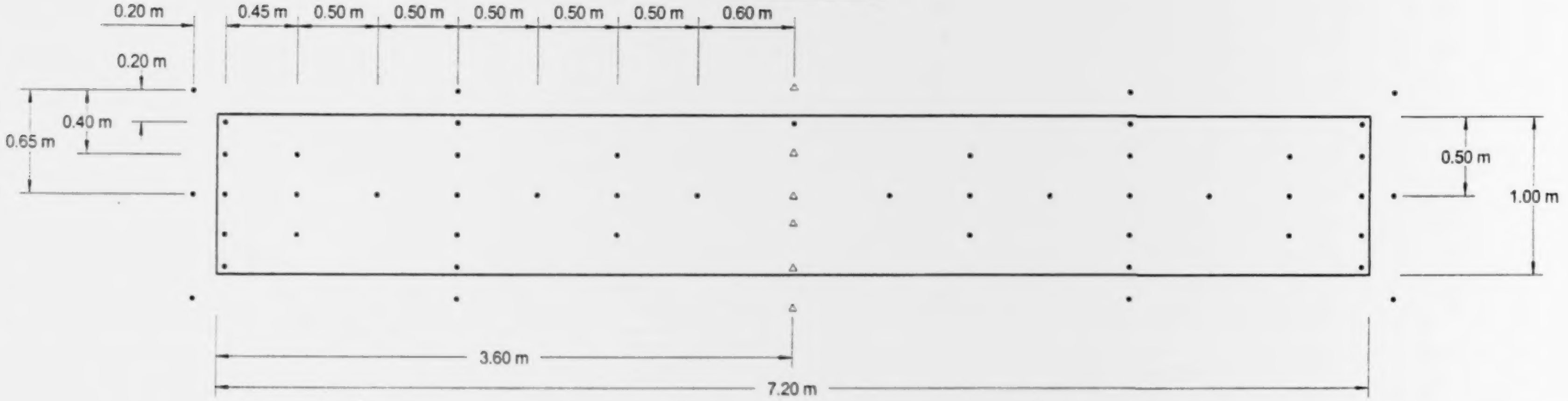
Date: 10/07/06
Scale: 1:75

Small axial defect


0.20 m
0.45 m
0.50 m
0.50 m
0.50 m
0.50 m
0.50 m
0.60 m
0.20 m
0.40 m
0.25 m
0.50 m
3.60 m
7.20 m

△ Array wall thermocouples - vertical distances differ from specific defect thermocouples
- Defect wall thermocouples
Vertical center of defect is aligned with 90% fill level
Horizontal center of defect is aligned with thermocouple array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

Medium axial fault


0.20 m
0.45 m
0.50 m
0.50 m
0.50 m
0.50 m
0.50 m
0.60 m
0.20 m
0.40 m
0.65 m
0.50 m
1.00 m
3.60 m
7.20 m

△ Array wall thermocouples - vertical distances differ from specific defect thermocouples
- Defect wall thermocouples
Vertical center of defect is aligned with 90% fill level
Horizontal center of defect is aligned with thermocouple array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

Insulation Defect Layout and Thermocouple Positions

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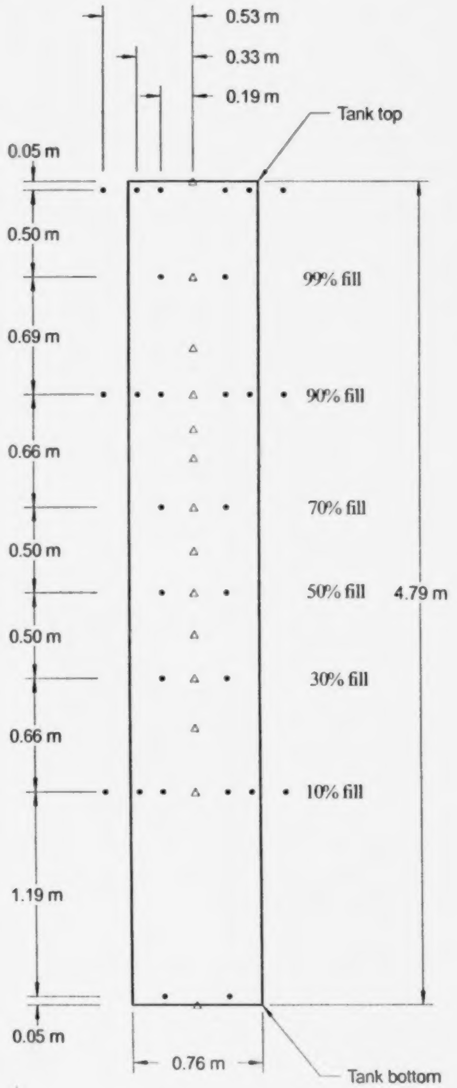
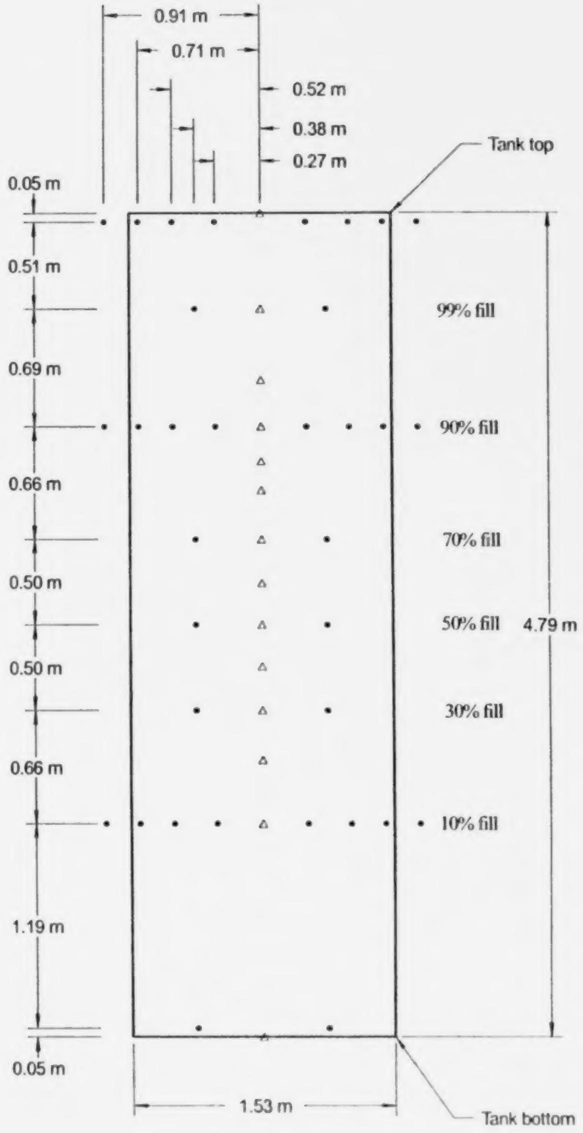
	Vs.: 1	Sheet: 1 of 2
	Date: 10/07/06	Scale: 1:40

Small Circumfrential Defect


0.53 m
0.33 m
0.19 m
Tank top
0.05 m
0.50 m
99% fill
0.69 m
90% fill
0.66 m
70% fill
0.50 m
50% fill
4.79 m
0.50 m
30% fill
0.66 m
10% fill
1.19 m
0.05 m
0.76 m
Tank bottom

Medium Circumfrential Defect


0.91 m
0.71 m
0.52 m
0.38 m
0.27 m
Tank top
0.05 m
0.51 m
99% fill
0.69 m
90% fill
0.66 m
70% fill
0.50 m
50% fill
4.79 m
0.50 m
30% fill
0.66 m
10% fill
1.19 m
0.05 m
1.53 m
Tank bottom

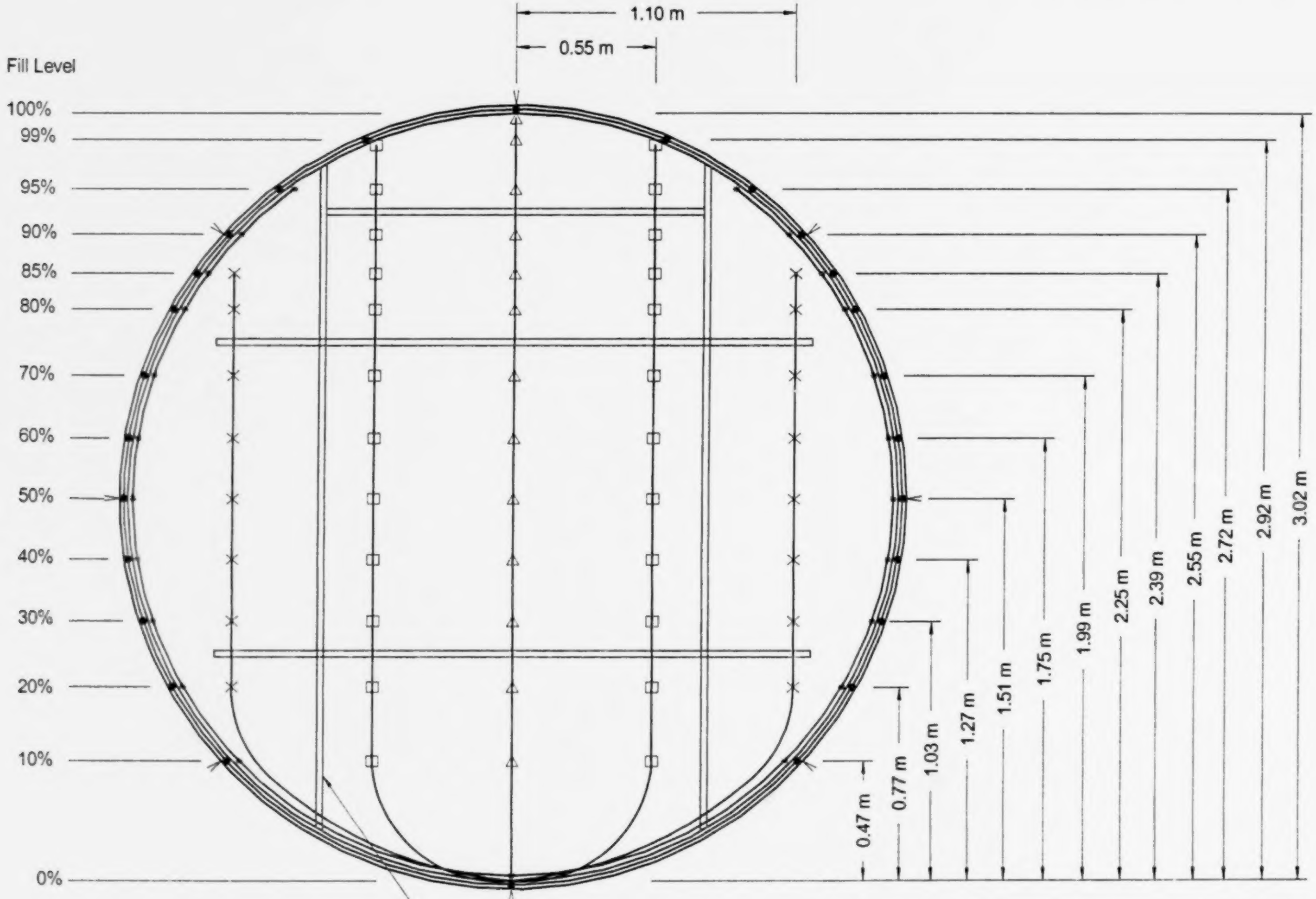
△ Array wall thermocouples
• Defect wall thermocouples
Vertical length spans one side of tank (top to bottom)
Horizontal center of defect is aligned with array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

△ Array wall thermocouples
• Defect wall thermocouples
Vertical length spans one side of tank (top to bottom)
Horizontal center of defect is aligned with array at downwind end of tank
Defect is shown flattened - distances are measured along outer tank wall

Insulation Defect Layout
and Thermocouple Positions

Drawn By:
Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

Dwg. No.: RT-TT-ID-01
Vs.: 1
Sheet: 2 of 2
Date: 10/07/06
Scale: 1:40


Fill Level
100%
99%
95%
90%
85%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1.10 m
0.55 m
0.47 m
0.77 m
1.03 m
1.27 m
1.51 m
1.75 m
1.99 m
2.25 m
2.39 m
2.55 m
2.72 m
2.92 m
3.02 m
Profile probes support
(1"x1" tube welded to tank)

- △ Centre profile probe TC element
- □ 99% profile probe TC element
- × 95% profile probe TC element
- ▪ Near wall profile probe TC element
- ● Tank wall TC (welded to outside of tank)
- ↗ Shell TC (welded to inside of shell)

Note:
Profile probes are attached to supports with rigid metal clamps for 1/4" tube
Top TC elements on centre and 99% profile probes are in the near wall position
Near wall profile probes are fastened to spacers welded to the tank wall

Lading, Wall and Shell Array Thermocouples

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Craig Davison
Dept. of Mech. & Mat. Eng.
Queen's University
Kingston, ON

Dwg. No.: RT-TT-AT-01
Vs.: 1
Sheet: 1 of 1
Date: 10/07/06
Scale: 1:25

Appendix B: Safety Factor Calculations for Rail Tank-Car Support

The worst case was used to verify that the rail tank-car supports, in the fire pan, could resist buckling, would not exceed the yield strength of steel, and that beam deflections would be insignificant. The calculations are summarised below. General assumptions are as follows:

1. Rail tank-car mass fully loaded 108,000 kg.
2. Weight is evenly distributed between the 8 wheels.
3. The rail is adequately designed to support the weight.
4. Yield strength of steel is σ_y=300 MPa.
5. Young's modulus of steel is E=200 GPa.

Only the calculations for the upper tubes are presented here, since the lower tubes had a more distributed load and larger factors of safety. These calculations are extremely conservative since they assume the entire load is on a single member, but, even if the original load produced this effect, as soon as elastic deformation began the load would be distributed over a larger area.

Buckling

Each wheel was located over one side of the square tube, so that the load was supported by the plate forming the side of the tube, as if it was a pinned column (K=1). The weight was distributed over the width of the rail. Figure B-1 is a free body diagram of this scenario. This results in a factor of safety of 5.1. The equations are:

$$I = \frac{1}{12} W^3 D = 2.2x10^{-8}\ m^4 \tag{4}$$

$$F_{cr} = \frac{\pi EI}{(KL)^2} = 663\ kN \tag{5}$$

$$\text{Factor of safety} = \frac{\mathrm{F_{cr}}}{F} = 5.1 \tag{6}$$

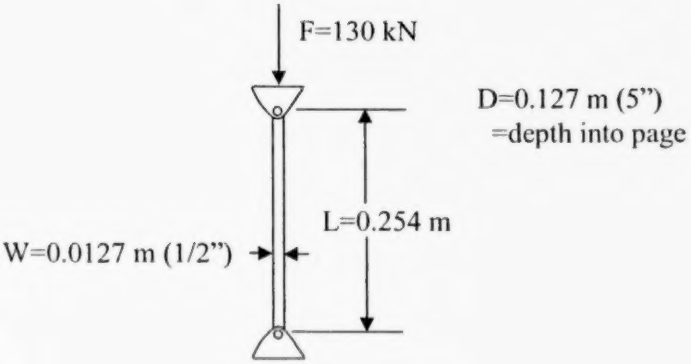

F=130 kN
D=0.127 m (5")
=depth into page
L=0.254 m
W=0.0127 m (1/2")

Figure B-1: Free body diagram for buckling of upper tube supporting rail tank-car

Yield Strength

The yield strength was calculated under the same assumptions as buckling and resulted in a safety factor of 3.7. The equations are as follows:

$$\sigma = \frac{F}{A} = \frac{F}{WD} = 81\,\text{MPa} \qquad 7$$

$$\text{Factor of Safety} = \frac{\sigma_y}{\sigma} = 3.7 \qquad 8$$

Appendix C: Rail Tank-Car Vent and Drain Simulations

To obtain the approximate time to depressurise the tank-car the vapour release was modeled under the following assumptions:

1. Vapour and liquid inside the tank-car are always in equilibrium and saturated.
2. Discharge coefficient of pipe system is 0.6.
3. Flow through pipe is single phase vapour.
4. Tank-car is initially 50% full.
5. Initial tank-car pressure is 1934 kPaG gauge (280.5 PSIG).

Other cases were run to examine alternate scenarios. They were the same as the base case above with the following changes:

1. Shell full – tank-car is initially 100% full, maximum initial mass with peak energy content.
2. Ambient – tank-car is initially 95% full and at 20°C, maximum initial propane mass.
3. Isentropic flow – discharge coefficient is 1 (i.e. isentropic flow through pipe system), fastest discharge rate.

Figure C-1 shows the tank-car pressure with time for each of these cases. The limiting case is the ambient. With its high mass content and low energy level it takes longer to depressurise the tank-car. It required over 2 hours too approach atmospheric pressure. The shell full case has the next largest initial mass and requires slightly less time than the ambient case. The isentropic case shows the effect of the flow resistance on venting time. It requires 40 minutes to reach atmospheric, versus 70 for the base case. The results could be refined if the discharge coefficient were experimentally determined for the vapour discharge system. This could be done by pressurising the tank-car with a gas and recording the pressure with time after the discharge line is opened, such as during the leak test. The remaining mass in the tank-car is important and is shown in Figure C-2.

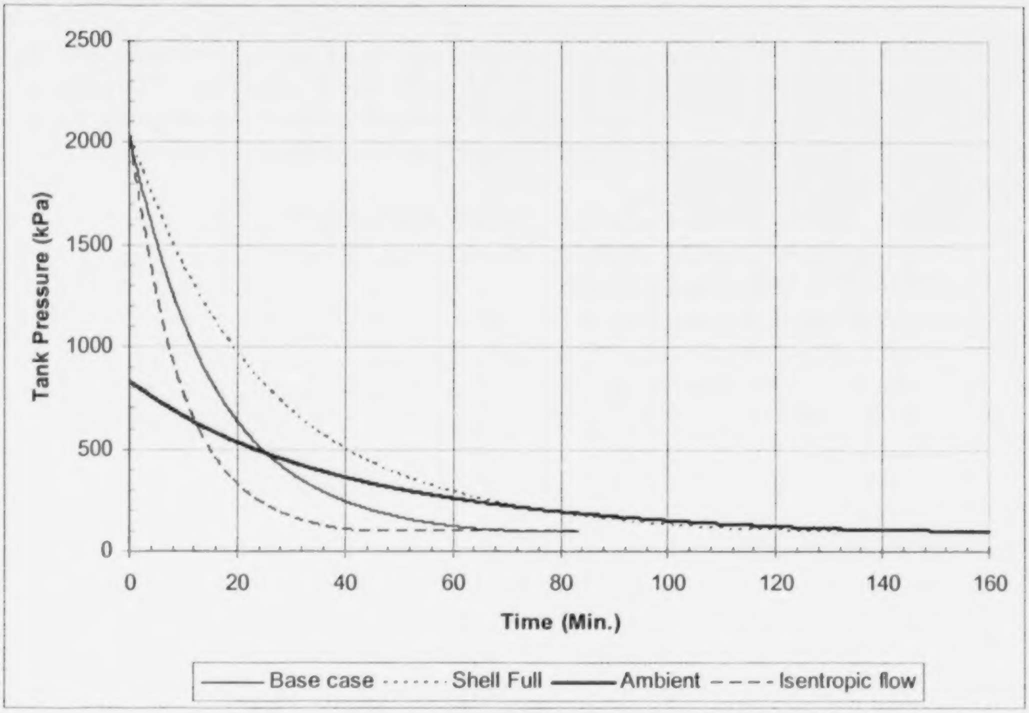


Figure C-1: Tank-car pressure after vapour discharge valve is opened

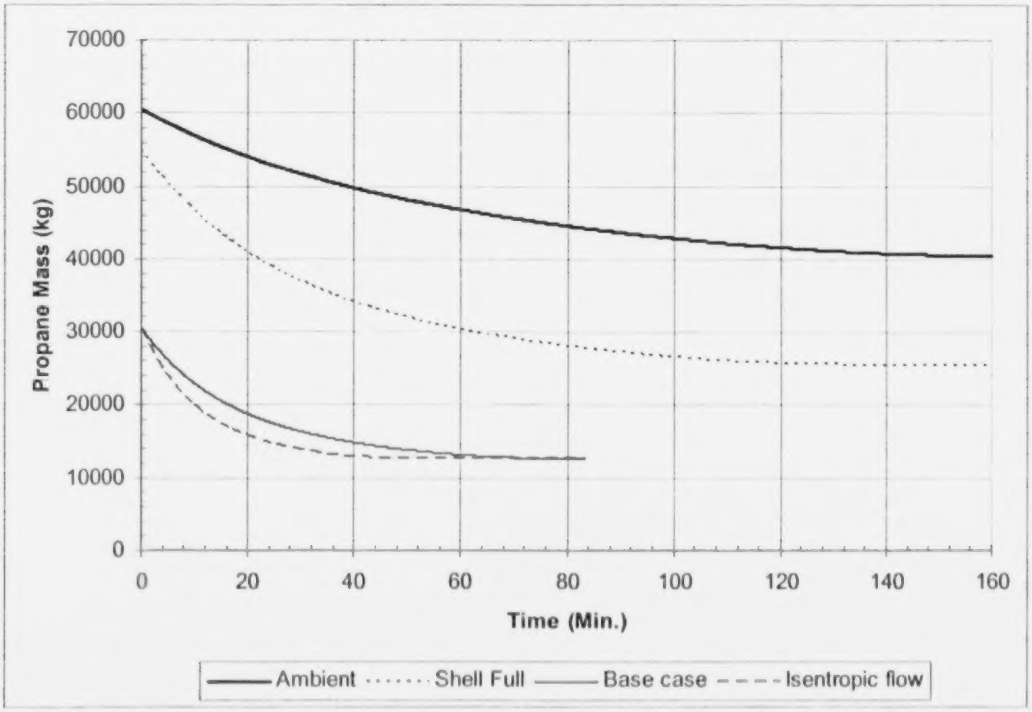


Figure C-2: Propane mass remaining in tank-car after vapour discharge valve is opened

Once the tank-car pressure has reduced to a safe level the liquid propane can be removed. This will be accomplished by gravity feed through a 5.1 cm (2 inch) pipe. The opening of this line will occur once the pressure has reduced to atmospheric, or very close to. The draining of the tank-car was modeled under the following assumptions to determine the time until the tank-car is empty:

1. Initial propane mass is 26,000 kg – propane mass remaining after vapour discharge to atmospheric pressure from shell full condition.
2. Line is 60 m long – design length.
3. Pipe diameter is 5.1 cm (2 inch).
4. Total minor loss coefficient is 3.4.
5. Tank-car pressure remains atmospheric – vapour discharge line is open.
6. Flow through vapour discharge line is negligible – heat transfer to tank-car is negligible.
7. Flow is single phase liquid – no boiling occurs in pipe.

Three additional cases were run for comparison:

1. Ambient – propane mass is 41,000 kg, mass remaining after ambient vapour discharge case, maximum mass to be drained.
2. 2 times minor losses – minor loss coefficient is doubled to determine effect on drain rate.
3. 3 inch pipe – pipe size is increased to 7.6 cm (3 inches) to determine effect on drain rate.

The results of the above simulations are given in Figure C-3. The base case required 4.1 hours to drain the tank-car. Doubling the minor losses has a small effect, increasing the drain rate to 4.4 hours. Increasing the pipe size, not surprisingly, significantly decreases the drain time to 1.5 hours. While this has the advantage of decreasing the time until the tank-car is emptied, it also increases the intensity of the fire required to burn-off the propane. The ambient case is the worst for mass content in the tank-car and requires just over 6 hours to drain. It is safe to assume 7 hours after opening the liquid drain the tank-car will be almost empty. However, it will contain propane vapour at atmospheric pressure.

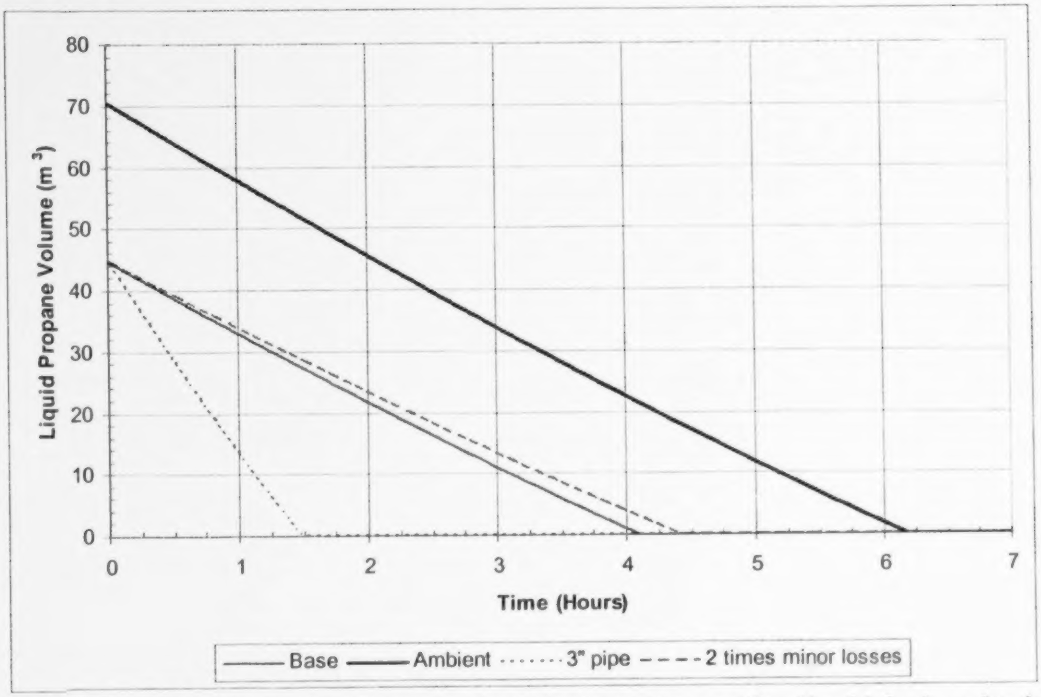


Figure C-3: Remaining liquid propane volume in tank-car after liquid drain valve is opened

Appendix D: Rail Tank-Car Purge Calculations and Simulations

Calculations for Standard Purge of 127 m^3 Tank-Car

This following calculation gives the mass of propane required to perform a standard purge on a 127 m^3 tank-car initially filled with air at 100 kPa and 20°C:

$$\begin{aligned} m &= \rho(p = 100\ kPa, T = 293\ K) * V_{\tan k} * 5 \\ &= 1.84\ kg/m^3 * 127\ m^3 * 5 \\ &= 234\ kg * 5 \\ &= 1170\ kg \end{aligned} \qquad 9$$

Each time the purge is performed the quantity of air is reduced by 50%, since half of the gas in the tank-car is removed. This results in the following fraction of air left in the tank-car after the complete process:

$$F_{air} = 0.5^5 = 0.03125 \qquad 10$$

Therefore, 3% of the tank-car volume is air and 97% is propane vapour. This corresponds to an air mass as follows:

$$\begin{aligned} m_{air} &= 0.03125 * \rho(p = 100\ kPa, T = 293\ K) * V_{\tan k} \\ &= 0.03125 * 1.2 * 127 \\ &= 4.8\ kg \end{aligned} \qquad 11$$

As the tank-car fills with liquid propane the air mass is compressed into a smaller space, increasing the pressure.

Purge Simulations

The standard purge simulation followed the purge procedure given in section 3.2 at an ambient temperature of 20°C, an inlet flow rate of 3.8 L/s (60 gallons/minute) and the valve requiring one second to close after the close pressure is reached.

Figure D-1 shows the modeled tank-car pressure during the fill procedure at three different ambient temperatures. The majority of the difference is due to the higher saturation temperature of the warmer liquid. The mass of air remaining and propane vented at different ambient temperatures is given in Figure D-2. Both the air remaining and propane vented increase with temperature. The worst case examined was 35°C, which had a Fraction_{air}=0.031 and vented 1.4% of the final propane mass in the tank-car. This is the same as fraction of air remaining after the standard purge. The propane vented is less than during the standard procedure.

Figure D-3 gives the tank pressure during fill with different vent open pressures. Figure D-4 shows the mass of air remaining and propane vented with increasing pressure above saturation to open the vent. As the open pressure increases the propane vented decreases but the air remaining increases. 700 kPa (100 PSI) was chosen since the propane vented does not decrease much beyond this point. This pressure also results in an acceptable mass of air remaining in the tank-car at the conclusion of the fill. The final open pressure on the plot is 2760 kPa (400 PSI). Since the tank-car never reaches this pressure during the fill all the venting is accomplished in the final step of the procedure, which lowers the tank-car pressure to 35 kPa (5 PSI) above the saturation pressure when the vent valve is opened. Adjusting the open pressure beyond this point will have no effect on the results, and this point is unobtainable since the PRV valve would have opened.

Figure D-5 shows the vented propane and air remaining as the final close pressure of the vent line is increased. The longer the valve is left open the more air and propane is removed. The accuracy of the pressure and temperature sensors will cause the result to vary from the desired 35 kPa but the remaining propane and air will still be acceptable. Figure D-6 shows that the propane fill rate will not significantly affect the amount of propane vented or remaining air. Figure D-7 shows that the vent line discharge coefficient also has little effect on the result. This is useful, since the discharge coefficient is not well defined.

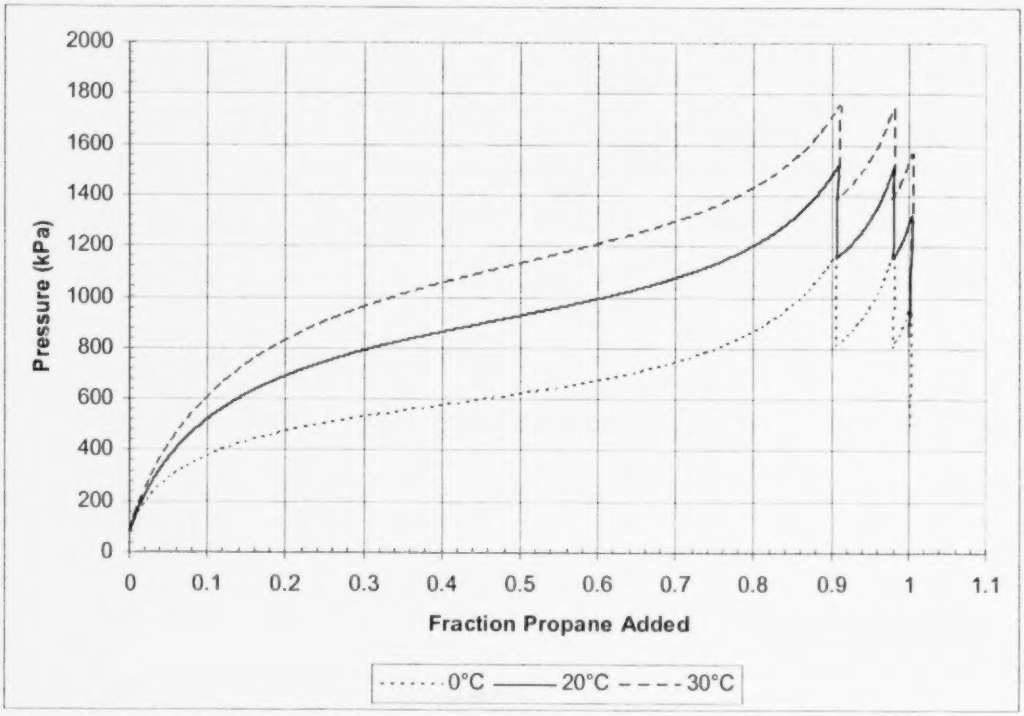


Figure D-1: Modeled tank-car pressure during fill procedure at 0, 20 and 30°C ambient temperature

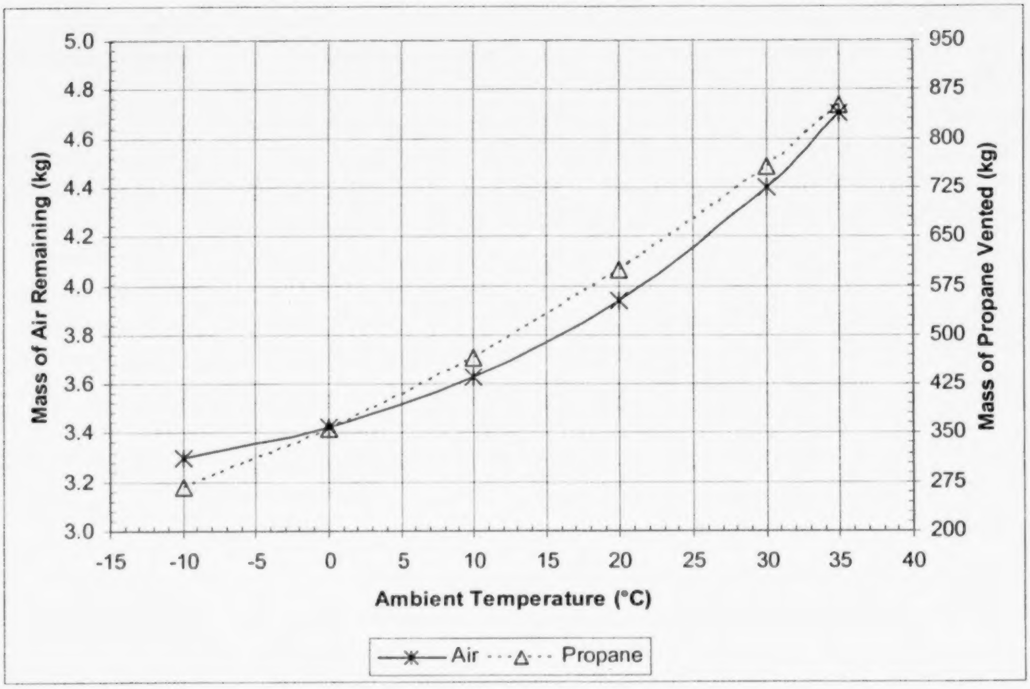


Figure D-2: Mass of air remaining and propane vented from tank-car at conclusion of purge/fill procedure with ambient temperature

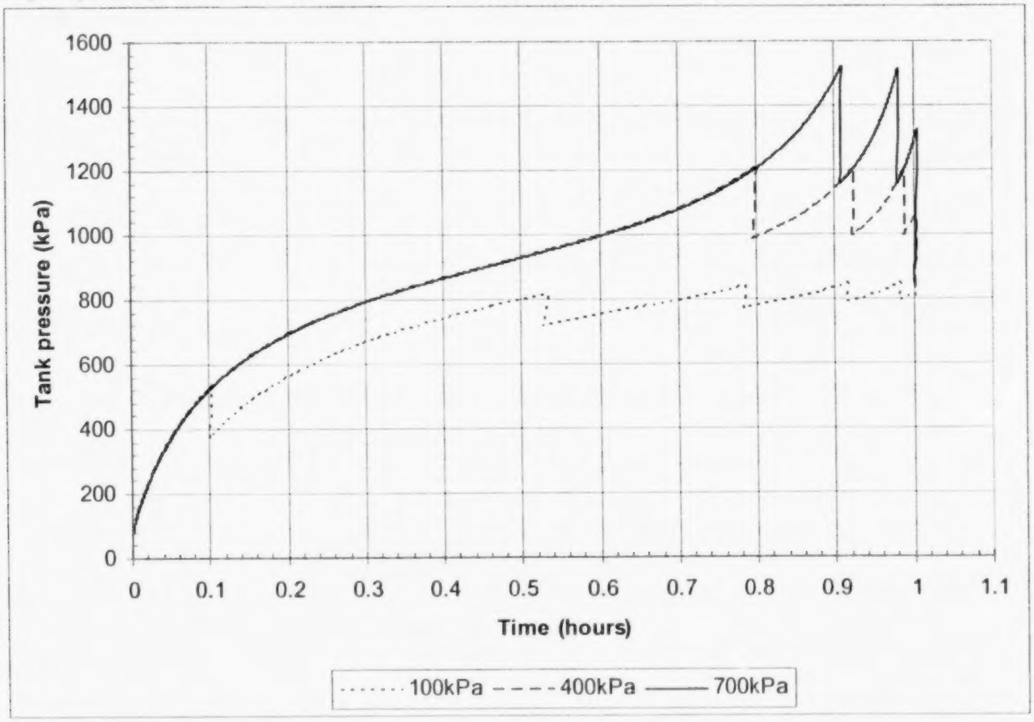


Figure D-3: Modeled tank-car pressure during fill procedure with vapour vent valve opened at 100, 400, 700 kPa above saturation and closed at ½ open pressure

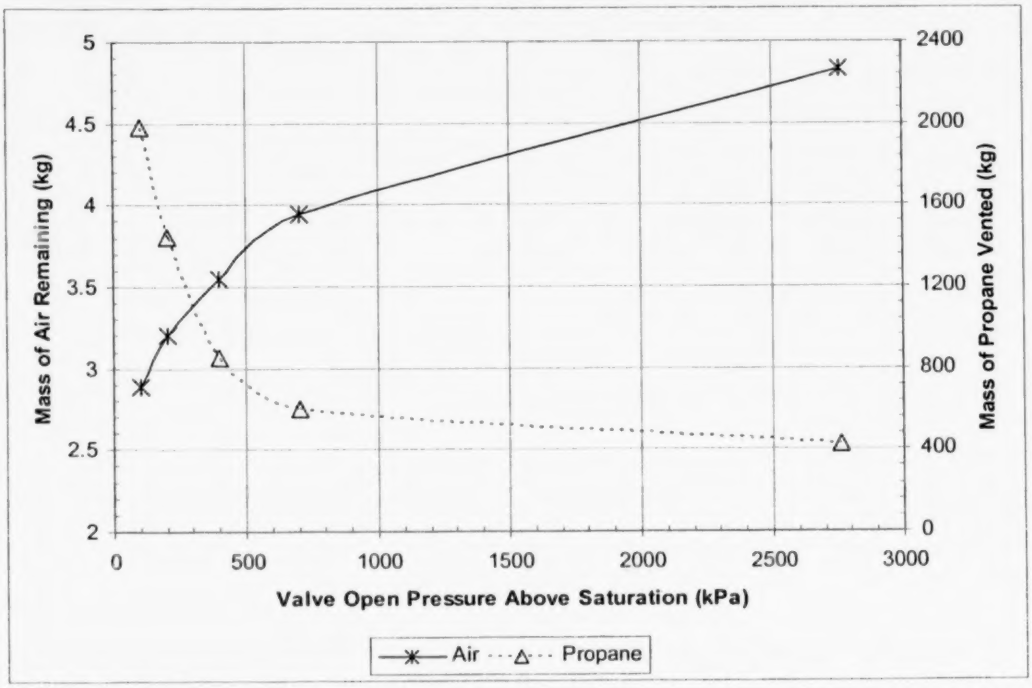


Figure D-4: Mass of air remaining and propane vented from tank-car at conclusion of purge/fill procedure with vent valve open pressure (valve closes at ½ open pressure)

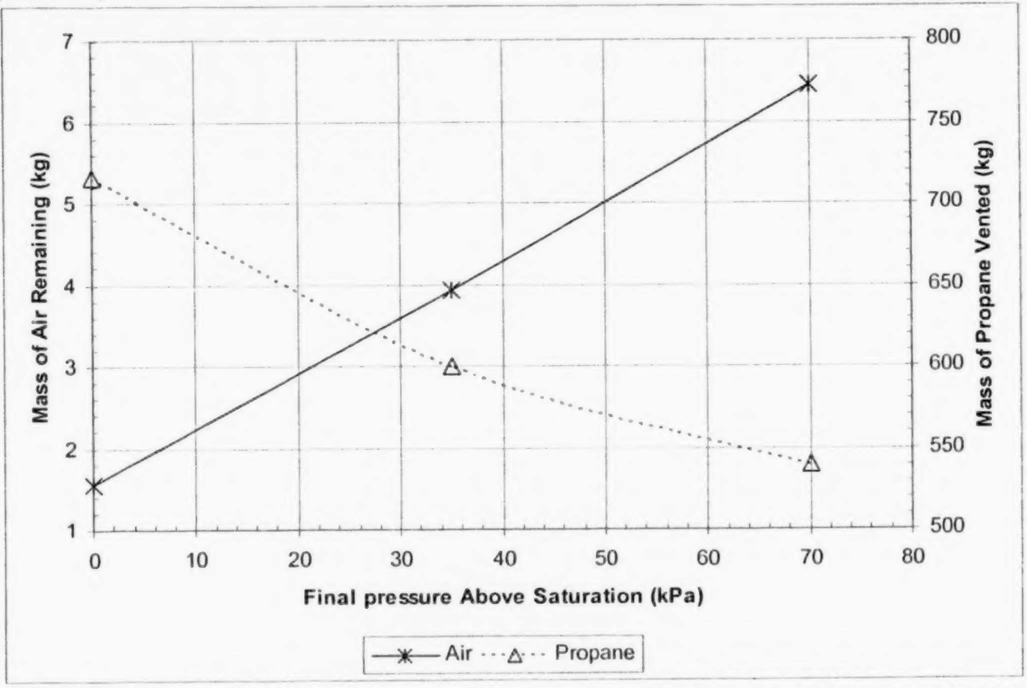


Figure D-5: Mass of air remaining and propane vented from tank-car at conclusion of purge/fill procedure with vent valve final close pressure

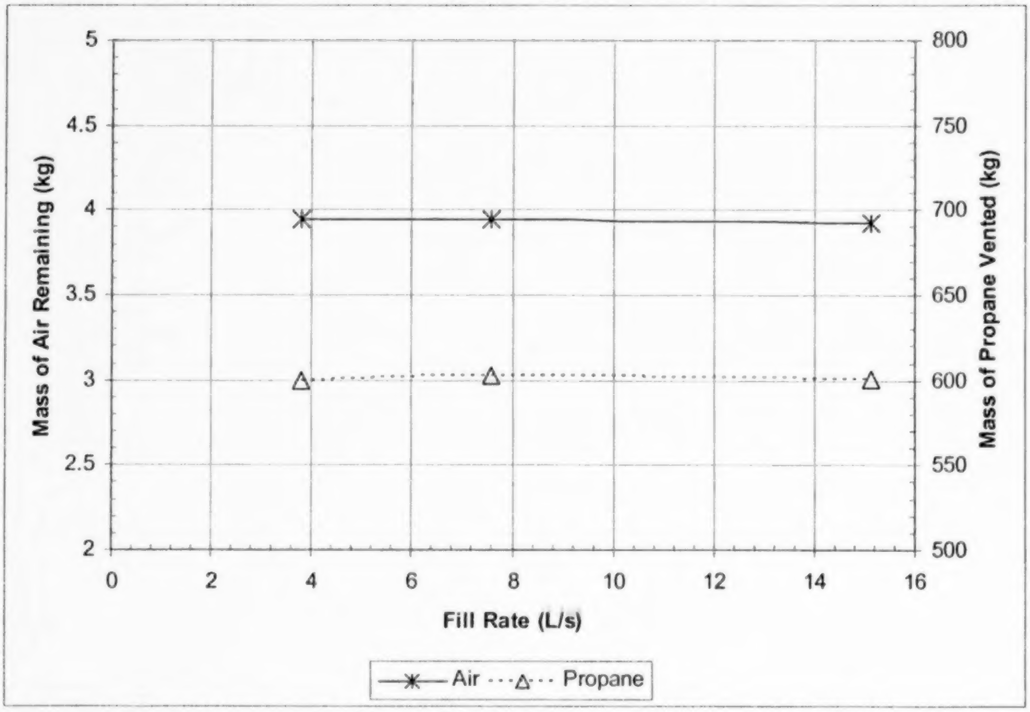


Figure D-6: Mass of air remaining and propane vented from tank-car at conclusion of purge/fill procedure with propane fill rate

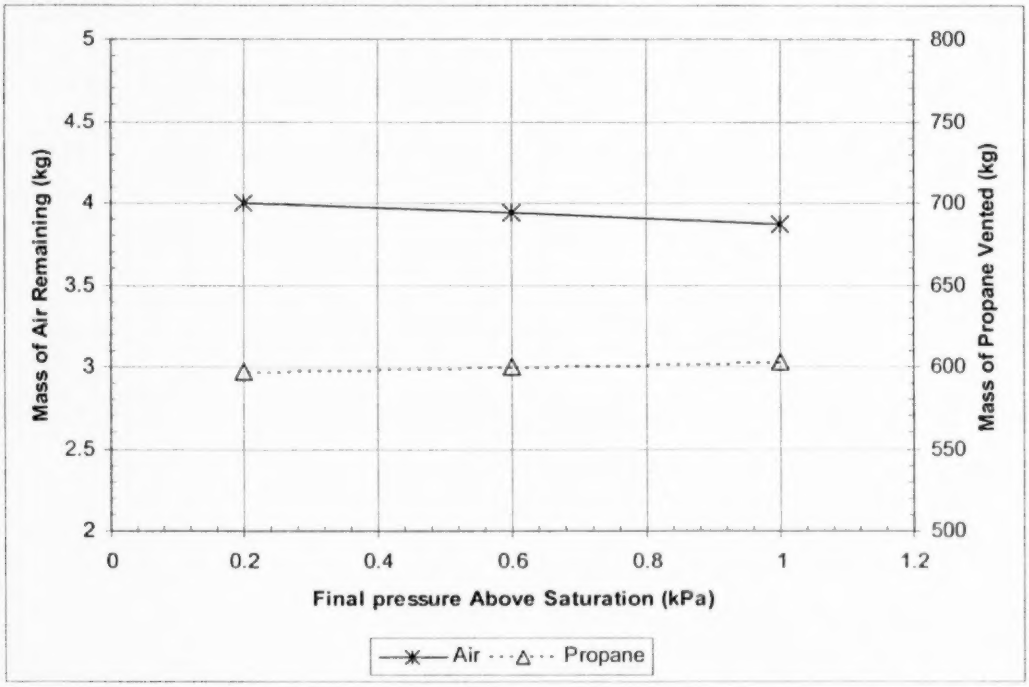


Figure D-7: Mass of air remaining and propane vented from tank-car at conclusion of purge/fill procedure with vapour vent line discharge coefficient

Appendix E: Blast and Thermal Hazard Calculations for Rail Tank-Car BLEVE Failure

Hazard Calculations

The first assessment of the blast damage modeled the detonation as a vapour cloud explosion and assumed all the propane in the tank-car was involved. The blast measure is calculated with equation 12.

$$C = \frac{r}{m_{propane}} \qquad 12$$

r = radius from tank in m

$\mathrm{m}_{\mathrm{propane}}$ = propane mass in kg

An alternate method of calculating blast damage uses the energy in the pressurised vapour to estimate the maximum overpressure of the blast wave. The energy available in the tank-car is given by equation 13. This energy is modified, by equation 14, to account for energy used in fracturing the tank-car. The overpressure is then given by equation 15 (Balke et al., 1999).

$$E_o = p_{\mathrm{tank}} V_{\mathrm{tank}} \left(\ln \frac{p_{\mathrm{tank}}}{p_{atm}} - 1 + \frac{p_{\mathrm{atm}}}{p_{\mathrm{tank}}} \right) \quad [J] \qquad 13$$

p_{tank} = tank pressure at failure in Pa

$\mathrm{p}_{\mathrm{amb}}$ = ambient pressure in Pa

$\mathrm{V}_{\mathrm{tank}}$ = Vapour volume in m^3

$$E = 0.6 E_o \quad [J] \qquad 14$$

$$\Delta p = p_{atm} \left(\frac{7a}{r^3} + \frac{2.7a^{0.66}}{r^2} + \frac{0.84a^{0.33}}{r} \right) \quad [Pa] \qquad 15$$

$$a = \frac{E}{4.3 \times 10^6}$$

Thermal radiation from the fireball is an additional hazard from ruptured propane tank-cars. This is created by the combustion of the propane remaining in the tank-car at failure. The most severe effect of the fireball is caused to the area engulfed, but locations beyond the fireball also receive a significant exposure to thermal radiation, especially when the duration of the fireball is accounted for. The radius of the fireball is given by equation 16, the duration by 17 and the total radiative heat load by 18.

$$r_{fireball} = 2.9 m_{propane}{}^{1/3} \quad [m] \tag{16}$$

$m_{propane}$ = Propane mass in kg

$$t = 0.0045 m^{1/3} \quad [s] \tag{17}$$

$$Q_f = t \times E \times F \times T \quad \left[kJ / m^2\right]$$

$E = 270\,\left[\mathrm{kW/m^2}\right]$ Strength of surface radiation from fireball

$$\mathrm{F} = r_{fireball}^2 \frac{r_{\text{from tank}}}{\left(r_{fireball}^2 + r_{\text{from tank}}^2\right)^{3/2}} \tag{18}$$

$T = 1 - 0.058 \ln r_{\text{from tank}}$ Transmissivity of air

Summary and Comparison of Hazards

The blast and thermal hazards at the significant test locations are summarised in Table E-1. For comparison Table E-2 shows the blast hazards calculated with the same techniques for the 1900 L (500 gallon) tank PRV trials (Birk et al., 2003) and thermal defect testing (Birk et al., 2005) performed by Birk and his team. During these tests the fuel tank and instrument bunker were shielded by concrete blocks, and personnel at the control bunker observed the tests in the open with no protection.

Most of the hazards should scale with the cube root of the mass of the propane. Assuming tanks are 50% full when they BLEVE, the hazards from a full-scale tank-car should reach about four times that of the 500 gallon tank.

Table E-1: Thermal and blast hazards at bunkers, fuel tanks and uncontrolled area for BLEVE of rail tank-car

Fill Level:		95%			50%			20%			5%		
Fireball radius (m):		114			92			68			43		
Duration of fireball (s):		18			14			11			7		
Location	Radius from tank-car (m)	Blast (C)	Thermal radiation (kW/m^2)	Total heat flux (kJ/m^2)	Blast (C)	Thermal radiation (kW/m^2)	Total heat flux (kJ/m^2)	Blast (C)	Thermal radiation (kW/m^2)	Total heat flux (kJ/m^2)	Blast (C)	Thermal radiation (kW/m^2)	Total heat flux (kJ/m^2)
Instrument bunker	50	1.3	Engulfed	-	1.6	Engulfed	-	2.1	Engulfed	-	3.4	66.9	442.6
Fuel tank	200	5.1	39.8	702.0	6.3	29.6	422.2	8.6	18.2	191.3	14	8.0	52.6
Control bunker	1000	26	2.1	36.3	32	1.3	19.2	43	0.7	7.7	68	0.3	1.9
Visitor bunker	2000	51	0.5	8.6	63	0.3	4.5	86	0.2	1.8	136	0.1	0.5
Uncontrolled area	3000	77	0.2	3.7	95	0.1	1.9	129	0.1	0.8	204	0.0	0.2

Table E-2: Thermal and blast hazards at bunkers and fuel tanks for BLEVE of 1900 L (500 gallon) tank

Fill Level:		80%			50%			20%			5%		
Fireball radius (m):		26			23			17			11		
Duration of fireball (s):		4			4			3			2		
Location	Radius from tank (m)	Blast (C)	Thermal radiation (kW/m^2)	Total heat flux (kJ/m^2)	Blast (C)	Thermal radiation (kW/m^2)	Total heat flux (kJ/m^2)	Blast (C)	Thermal radiation (kW/m^2)	Total heat flux (kJ/m^2)	Blast (C)	Thermal radiatio n (kW/m^2)	Total heat flux (kJ/m^2)
Instrument Bunker	35	3.8	62.2	255.4	4.5	53.1	186.3	6.1	35.8	92.6	9.7	17.0	27.6
Fuel tank	100	11	12.5	51.4	13	9.4	33.0	17	5.3	13.7	28	2.1	3.5
Control bunker	330	36	1.1	4.7	42	0.8	2.9	57	0.5	1.2	91	0.2	0.3

Appendix F: Ground Heating Simulations

Modeling of ground heating was done to determine the depth required to protect the equipment. The fire was modeled as a blackbody emitter at 1027°C. The upper limit of the specified fire temperature is 871+56=927°C. Since a pool fire is uncontrolled, an extra 100°C was added to the model to produce conservative results. During the heating stage no convection at the ground surface was accounted for and the view factor of the ground to the fire was treated as a differential element centred on a perpendicular rectangle 24 m wide by 18 m high. Although the fire will not be a rectangle this was considered good enough to approximate the depth required. The rectangle assumption will produce conservative results. The remaining view from the ground sees the surroundings at 20°C. Ground heating was modeled adjacent to the fire pan, 50 m from the fire pan at the instrument bunker, and engulfed in the pool fire, which would be seen downwind of the fire pan.

The pool fire was assumed to last for 120 minutes and at the conclusion the tank-car BLEVEed, generating a fireball that engulfs the ground for 20 seconds. During the fireball the view factor to the fire was adjusted to 1. After the fireball the ground was allowed to cool and a convective coefficient of 2 W/m^2-K was applied, in addition to radiative cooling. These values were all chosen to give conservative results; the ground is modeled at its hottest. For the same reason the ground material was assumed to be sand, which produced higher temperature profiles than soil. The properties of sand and soil were assumed constant with temperature. The properties used in the simulation are as follows:

Sand
C=800 J/kg-K (Specific heat)
k=0.27 W/m-K (Thermal conductivity)
ρ=1515 kg/m^3 (Density)
ϵ=0.76 (Normal total emissivity)

Soil
C=1840 J/kg-K (Specific heat)
k=0.52 W/m-K (Thermal conductivity)
ρ=2050 kg/m^3 (Density)
ϵ=0.66 (Normal total emissivity)

The properties are from Incropera and DeWitt (1996) except for emissivities, which are from Siegal and Howell (1992).

The surface temperatures at three locations, engulfed by, adjacent to and 50 m from the pool fire, are given in Figures F-1 and F-2. Figures F-1 shows the heating of the surface. The engulfed practically reaches the fire temperature, the adjacent is 200°C below the fire temperature, and at 50 m distant the ground is heated to just over 100°C. The two non-engulfed locations show a spike in temperature when they are engulfed by the fire ball. This is especially noticeable at the 50 m location which jumps over 600°C in the 20 second fireball. However, the grounds good insulating properties prevent the heat from penetrating deeply and, once the fireball is extinguished, it is quickly dissipated.

The cooling process is shown Figures F-2, and the same insulating properties that help the earth protect the cables and equipment make it slow to cool down. This simulation is conservative and shows the ground adjacent to the fire pan is still warm after 24 hours. To ensure safety of personnel no one should approach closer than the instrument bunker until 10 hours after a full length test.

Figures F-3 is the temperature profile after 120 minute pool fire and a 20 second fireball at the instrument bunker. The spike in temperature due to the fireball penetrates less than 1 cm into the ground. The figure shows the profile for both sand and soil, and the sand has the higher temperature. The figure shows the profile on two scales. The full-scale covers the entire temperature range while the low range shows the deeper earth in more detail. At a 10 cm depth the temperature is less than 30°C. The most extreme case is engulfed, shown in Figures F-4, this provides the limit on depth required to protect cables and instruments. In this case, 20 cm deep the temperature has maintained 20°C, which indicates it has not been affected by the fire. Applying a margin of safety, all cables and instruments will be buried 30 cm deep out to the instrument bunker. From the instrument bunker out to 150 m the cables will be under 10 cm. To protect from thermal radiation from the fire ball, the cables will be under 2 cm out to 400 m and, as a precaution, be covered out to 600 m, where the firebreak is located.

The surface emissivity affects the rate of heat transfer to the ground and will vary depending on ground cover. Near the pool fire it could approach 1 as soot coats the surface. Figures F-5 shows the temperature profile adjacent to the pool fire at the conclusion of the test for sand and soil with their listed surface emissivities and with emissivities of 1. The worst case is sand with an emissivity of 1. However, the difference is not significant. The 70°C isotherm penetrates only 2 cm deeper, and the temperature is within 5°C of ambient at 16 cm, 14 cm before the recommended depth to bury cables and equipment.

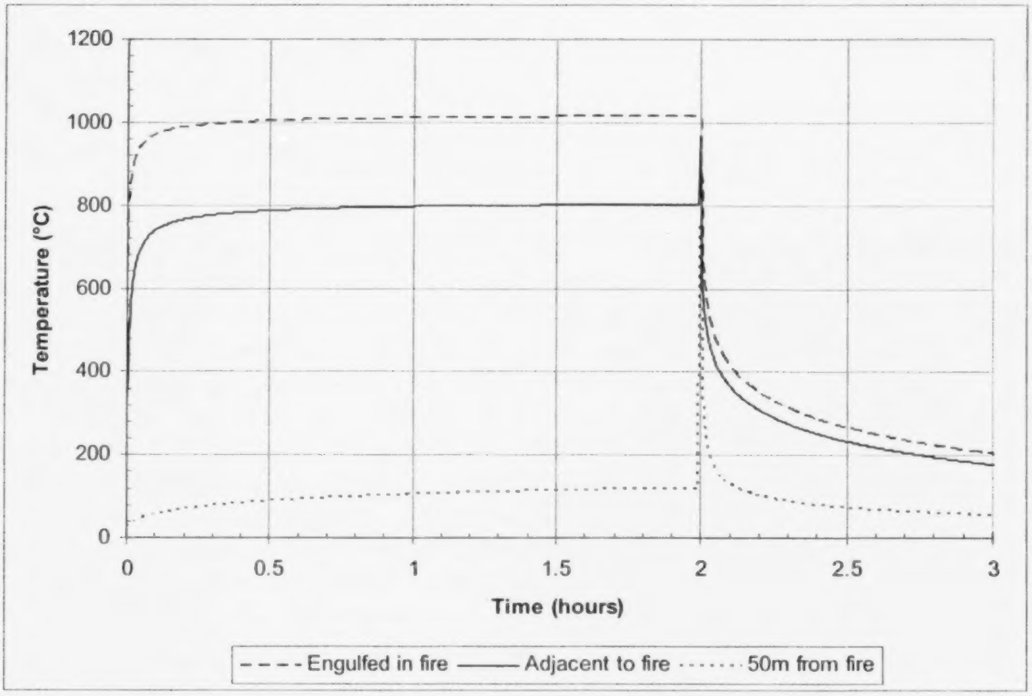


Figure F-1: Surface temperatures of sand engulfed, adjacent and 50 m from pool fire during heating and initial cooling

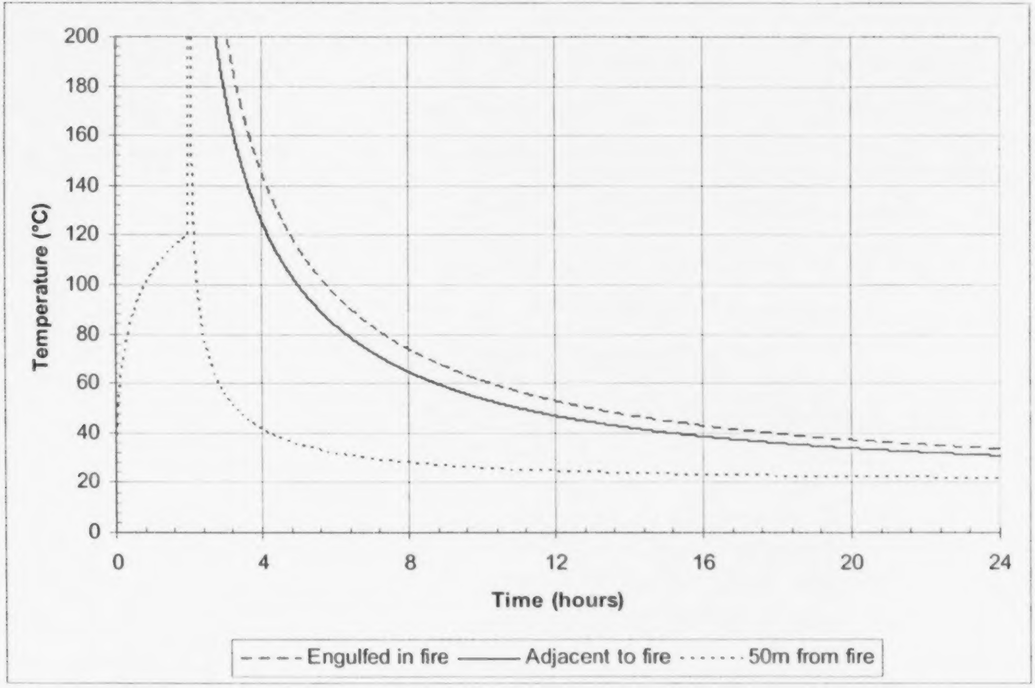


Figure F-2: Surface temperatures of sand engulfed, adjacent and 50 m from pool fire during heating and cooling (scaled to show details of cooling)

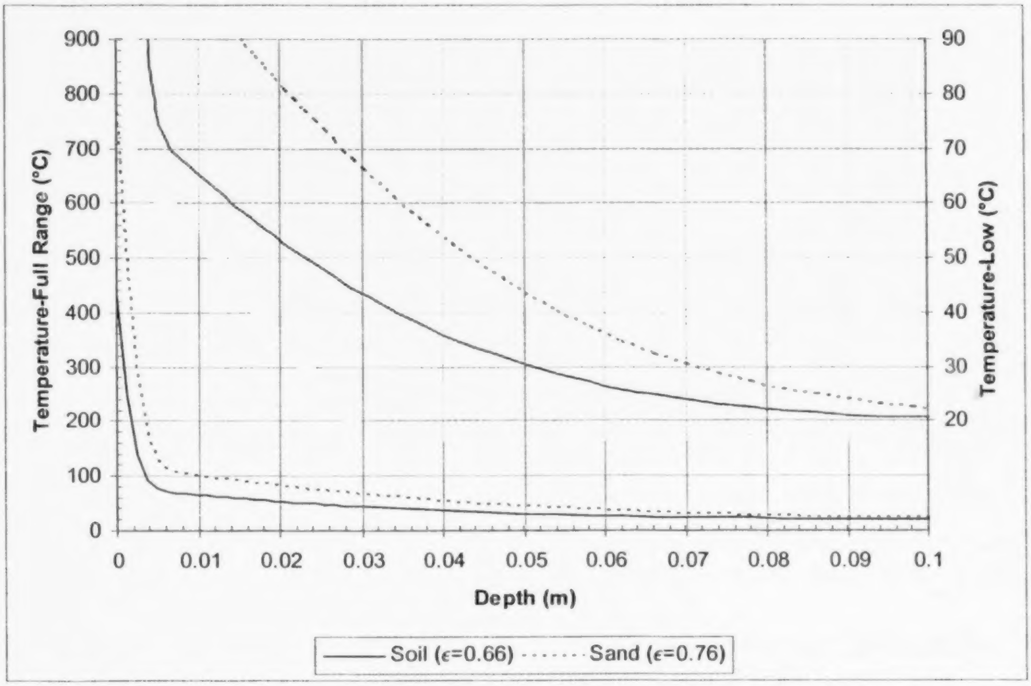


Figure F-3: Ground temperature profile at 50 m distance from pool fire at conclusion of test and 20 second fireball for different ground materials (repeated on two scales)

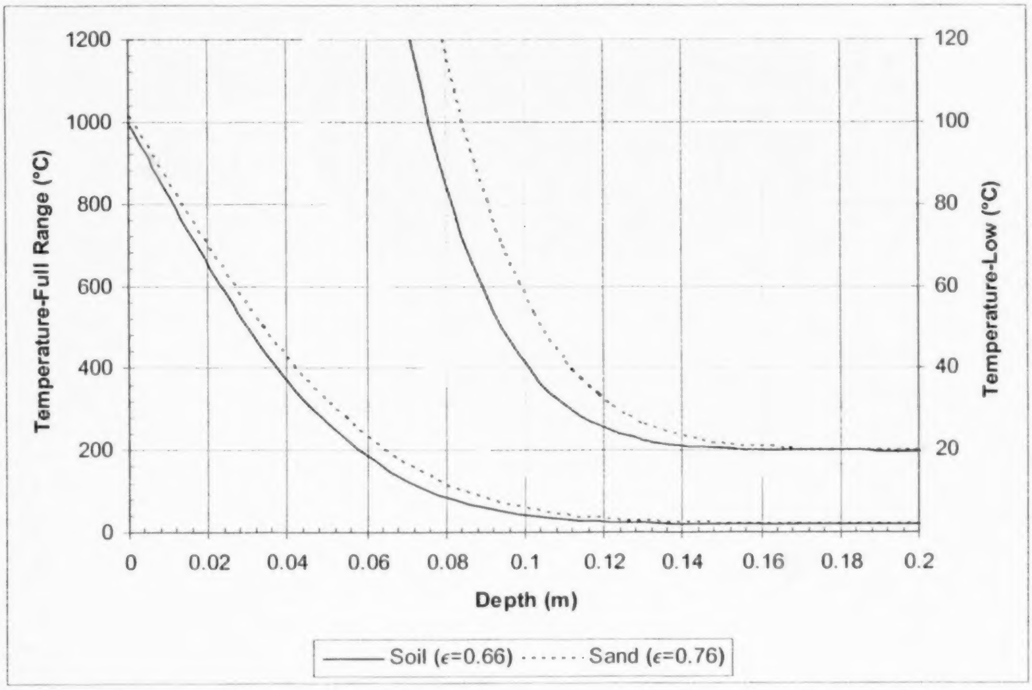


Figure F-4: Ground, engulfed in fire, temperature profile at conclusion of test and 20 second fireball for different ground materials (repeated on two scales)

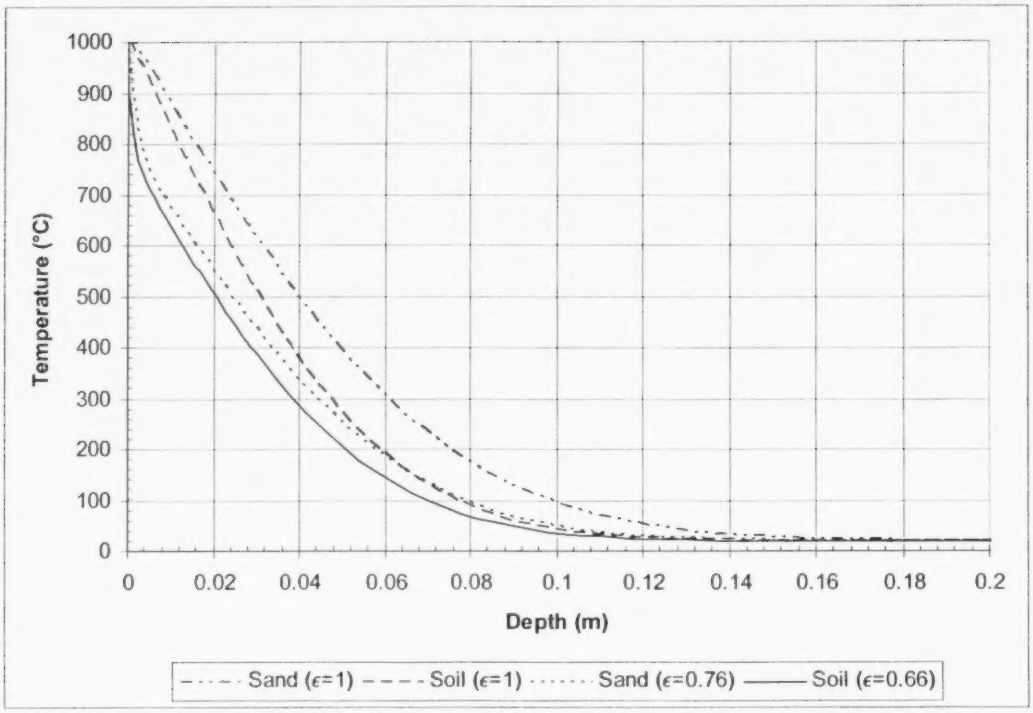
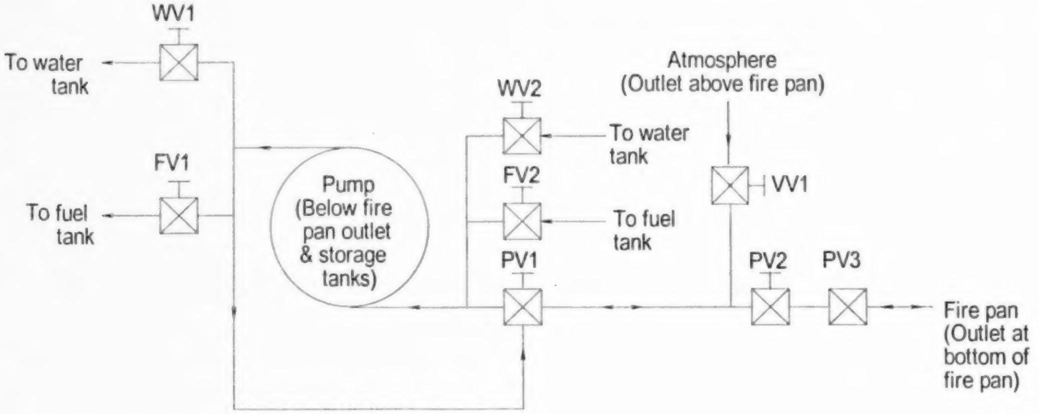


Figure F-5: Ground temperature profile adjacent to pool fire at conclusion of test and 20 second fireball for different ground materials and surface emissivities

Appendix G: Dual Function Fuel and Water Makeup Valve System

If the water make up option is not used, or both the water and fuel pumps are specified to handle both liquids, a set of valves will be required to direct the pump inlet and outlets to the correct locations. In addition, a vent to atmosphere will be required near the fire pan, to allow the JP-4 in the piping to be returned to the fuel tank prior to pumping the water out of the fire pan. These valves could be manually or remotely operated. The valve system will be required to allow the pumping of fuel or water, to and from, the fire pan. A schematic of the system is given in Figures G-1. The valve settings to perform the various pumping functions are given in Table G-1. The settings to allow fuel to flow during the test are highlighted. In addition to removing water after the test this system can remove rain water that has collected in the fire pan.


WV1
To water tank
Atmosphere (Outlet above fire pan)
WV2
To water tank
FV1
FV2
VV1
To fuel tank
Pump (Below fire pan outlet & storage tanks)
To fuel tank
PV1
PV2
PV3
Fire pan (Outlet at bottom of fire pan)

WV1 - Manual water pump outlet valve
WV2 - Manual water pump inlet valve
FV1 - Manual fuel pump outlet valve
FV2 - Manual fuel pump inlet valve
PV1 - Manual 3 way valve directing flow from fire pan to pump inlet or outlet
PV2 - Manual fire pan shut off valve
PV3 - Automated fire pan shut off valve
VV1 - Manual vent valve to allow pumping pipeline dry

Figure G-1: Schematic of multifunction pumping and valve system

Table G-1: Valve positions to perform required pumping functions for multifunction system

Valve	Fuel to Fire Pan	Water to Fire Pan	Drain Pipe of Fuel	Drain Fire Pan of Water	Notes
WV1	Closed	Closed	Closed	Open	Manual valve
WV2	Closed	Open	Closed	Closed	Manual valve
FV1	Closed	Closed	Open	Closed	Manual valve
FV2	Open	Closed	Closed	Closed	Manual valve
PV1	Outlet	Outlet	Inlet	Inlet	3-way valve connects fire pan to either pump inlet or outlet
PV2	Open	Open	Closed	Open	Manual valve
PV3	Open	Open	Closed	Open	Automated valve for control during test
VV1	Closed	Closed	Open	Closed	Manual valve

During the test the manual valves will be set for the "fuel to fire pan" function, and the automated fire pan valve opened and closed as required. The automated valve has to open prior to starting the pump and close after the pump has stopped. This will require a digital output from the DAC board. The components required for the fuel delivery system are given in Table G-2.

Table G-2: Fuel and water multifunction delivery system components

Component	Quantity
10.2 cm (4 inch) Piping	1
Pump 560 USGPM@92 ft. water head	1
25HP motor	1
10.2 cm (4 inch) Brass ball valves	5
10.2 cm (4 inch) 2-way valve	1
10.2 cm (4 inch) Brass ball valve	1
10.2 cm (4 inch) Solenoid valve	1

Appendix H: Instrument Well Modeling

These results are based on the following baseline instrument well specifications:

Inside diameter:	1.2 m
Inner and outer well wall:	1.2 mm thick (18 gauge) sheet steel
Well wall insulation:	13 cm (8 layers of Unifrax 1.6 cm ($^5/_8$ inch) thick tank-car insulation)
Blackbody fire temperature:	1000°C (1273 K)
Surface emissivities:	Outer well wall=0.95 Inner well wall=0.81 Exposed tank-car surface=0.81 Bottom of well=0.9

The bottom of the well was assumed to be perfectly insulated. The effect of varying some of these specifications is shown in Figure H-1. By reducing the well diameter the exposed tank-car is reduced relative to the well wall, and, therefore, the cooling capacity is also reduced, and the temperatures increase. Not surprisingly decreasing the insulation or increasing the fire temperature increases the well temperature. The largest increase in temperature occurs when the tank-car wall is insulated.

Figures H-2 shows the modeled well temperatures over the duration of the test. After 30 minutes the temperatures have reached equilibrium, and anything in the well must be able to withstand the maximum temperature for the remaining 70 minutes. The time for the fire to burn out after the fuel is shut down is not shown, but it should not exceed the equilibrium temperature.

Figures H-3 shows the well air temperature over the duration of the test for each of the cases shown in Figures H-1. All cases reach equilibrium by the midway point of the test. The slowest to reach equilibrium is the reduced well diameter which has a smaller area exposed to the fire. The fact that it also has a smaller exposed tank area cooling the well is demonstrated by the higher equilibrium temperature. This compares to Figures H-4, showing the well temperatures with an insulted tank wall in the well, which has most cases still increasing at the conclusion of the test, and all are significantly higher than the baseline case.

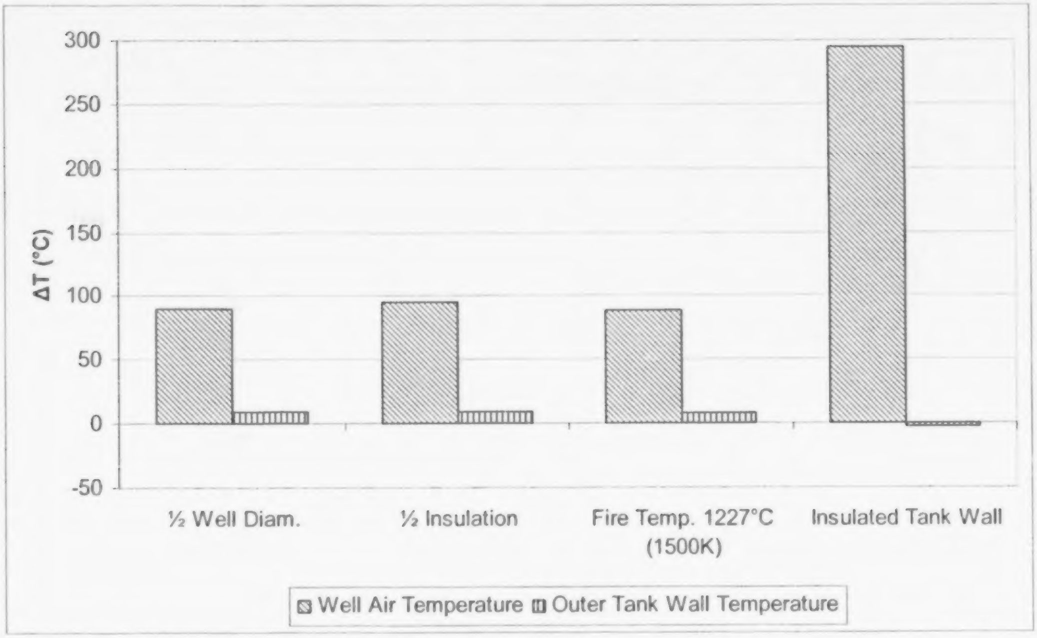


Figure H-1: Effect of varying instrument well specifications from baseline on well air and tank-car wall temperatures

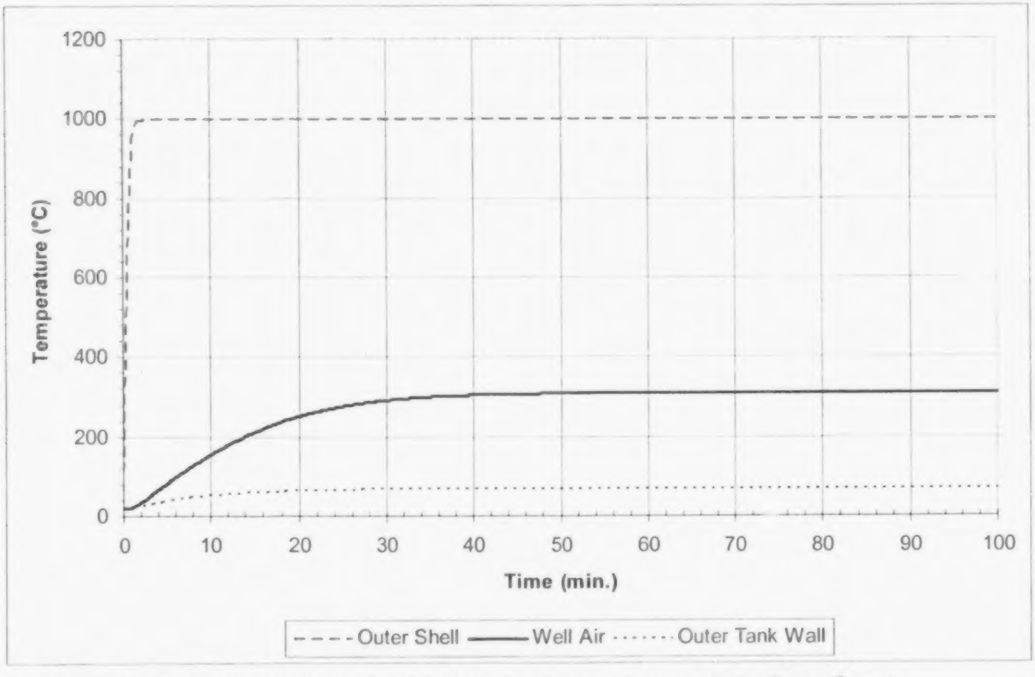


Figure H-2: Baseline instrument well temperatures over duration of test

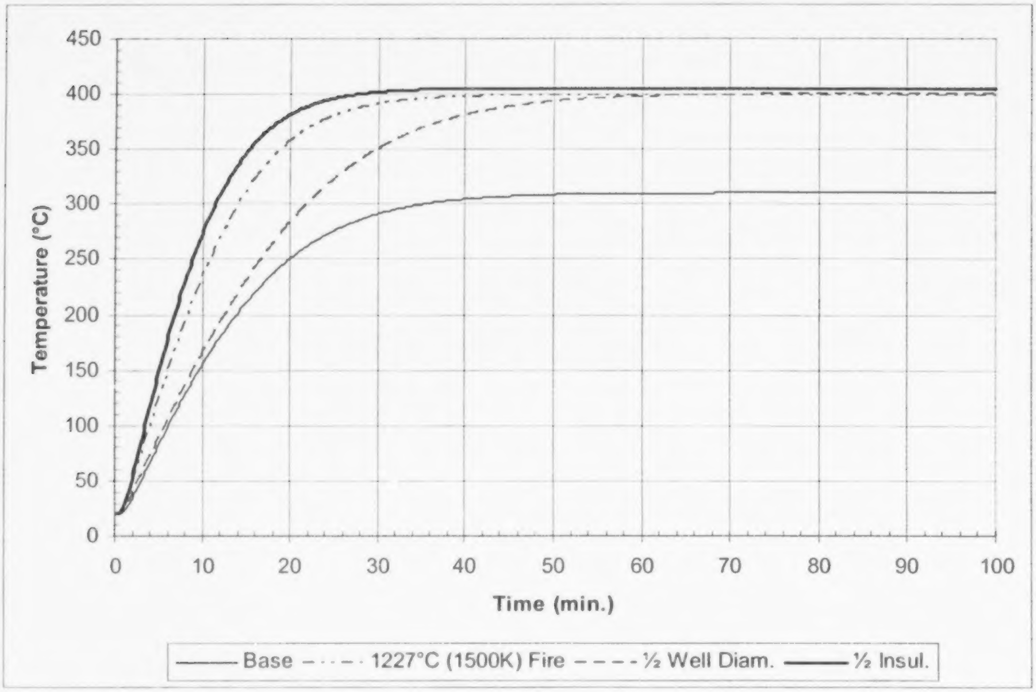


Figure H-3: Well air temperature over duration of test with variations from the baseline condition

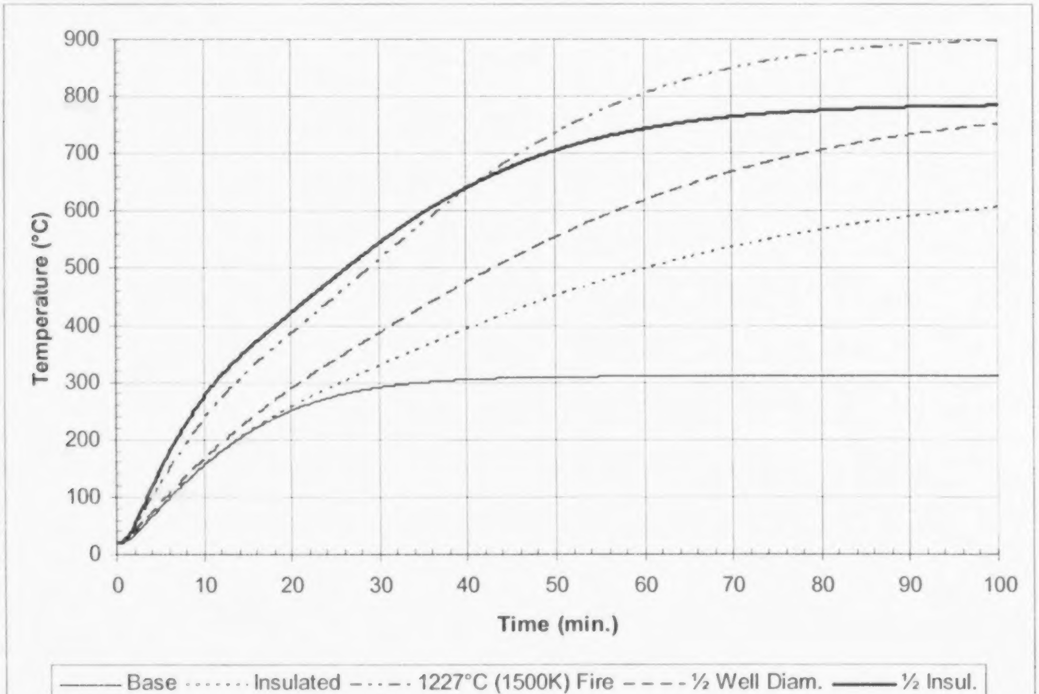


Figure H-4: Well air temperature over duration of test with variations from baseline condition, all variations include insulated tank wall inside the instrument well

Appendix I: Safe and Robust Control System Strategies

Two possible control systems are presented. The first is designed to maximise safety by defaulting to the safest setting. The second is designed for maximum test robustness. It defaults to the condition most likely to allow the test to either continue, or be resumed at a later time. Section 11.2 gives a control strategy that balances the two options presented here.

Maximum Safety

This control system is designed for maximum safety. The valves on the vapour vent and liquid drain are normally open. If the power fails the valves will open, releasing both the pressure through the vapour line and the liquid propane through the liquid drain line. Both the vapour and liquid drain systems also have a manual valve that remains in the closed position until just prior to the test.

The power relays controlling the vent and drain valves are activated through the following controls in series:

- Manual toggle switch in control bunker – this must be closed to close valve.
- Normally closed pushbutton in instrument bunker – for testing valve pressing this button will open the valve
- Vapour line can also be controlled by a computer controlled relay and toggle switch in the control bunker.

If the control power supply fails the power relay opens, cutting of power to the valves, which then open. If the electrical power supply fails the valves open. The action of the liquid drain valve is summarised in Table I-1 and the vapour vent valve in Table I-2.

The fuel control system is operated by the computer, but can be overridden manually. The fuel control valve is normally closed so that if power fails it will close and stop the flow. The fuel pump will stop operating if the power fails.

The water supply system is operated by the computer. This system is not critical to test control and can be shut down by either the pump or valve so no manual control is provided. Both the valve and pump are controlled through the computer. The valve relay must be activated before the pump relay. If power fails the pump will stop and the valve will close.

The power relays controlling the valve and fuel pump are activated through the following controls in series:

- Manual toggle switch in control bunker – this must be closed to open valve/run pump.
- Normally open computer controlled relay – this must be closed to open valve/run pump.
- For the fuel pump a normally open switch on the valve power relay – this must be closed to run pump to prevent pump operating with valve is closed.

If the control electrical supply fails the power relay opens, cutting power to the valve, which closes, and to the pump, which shuts down. If the power electrical supply fails then the valve closes and the pump stops. The action of the fuel valve is summarised in Table I-3 and the fuel pump in Table I-4.

The ignition and calorimeter pumps are controlled through the computer. They will be on/off switches in the DAC program. The DAC board outputs activate the power relays. The ignition system requires a relay for the fuel valve and the spark igniter. The calorimeter requires a relay to activate each pump. Manual control is included to activate remote still cameras. The cameras are activated by the following controls in parallel:

- Manual toggle switch in control bunker – when closed cameras are activated.
- Manual momentary pushbutton in control bunker – when pressed cameras are activated to allow for single shots of test.

Table I-1: Control status for liquid drain valve under safe strategy

Operating Power	**Control Power**	**Instrument Bunker Pushbutton**	**Control Bunker Toggle Switch**	**Valve Position**
Off	On/off	Open/Close	Open/Close	**Open**
On	Off	Open/Close	Open/Close	**Open**
On	On	Open	Open/Close	**Open**
On	On	Open/Close	Open	**Open**
On	On	Close	Close	**Close**

Note: Pushbutton is normally closed

Table I-2: Control status for vapour vent valve under safe strategy

Operating Power	**Control Power**	**Instrument Bunker Pushbutton**	**Control Bunker Toggle Switch 3**	**Control Bunker Toggle Switch 4**	**Computer Controlled Relay**	**Valve Position**
Off	On/off	Open/Close	Open/Close	Open/Close	Open/Close	**Open**
On	Off	Open/Close	Open/Close	Open/Close	Open/Close	**Open**
On	On	Close	Close	Open/Close	Open/Close	**Close**
On	On	Open/Close	Open/Close	Close	Close	**Close**
On	On	Open/Close	Open	Open/Close	Open	**Open**
On	On	Open	Open/Close	Open/Close	Open	**Open**
On	On	Open/Close	Open	Open	Open/Close	**Open**
On	On	Open	Open/Close	Open	Open/Close	**Open**

Note: Pushbutton is normally closed

Table I-3: Control status for fuel supply valve under safe strategy

Operating Power	Control Power	Computer Controlled Relay	Control Bunker Toggle Switch	Valve Position
Off	On/off	Open/Close	Open/Close	**Close**
On	Off	Open/Close	Open/Close	**Close**
On	On	Open	Open/Close	**Close**
On	On	Open/Close	Open	**Close**
On	On	Close	Close	**Open**

Note: Computer controlled relay is normally open

Table I-4: Control status for fuel pump under safe strategy

Operating Power	Control Power	Fuel Valve Relay	Computer Controlled Relay	Control Bunker Toggle Switch	Pump Status
Off	On/off	Open/Close	Open/Close	Open/Close	**Off**
On	Off	Open/Close	Open/Close	Open/Close	**Off**
On	On	Open	Open/Close	Open/Close	**Off**
On	On	Open/Close	Open	Open/Close	**Off**
On	On	Open/Close	Open/Close	Open	**Off**
On	On	Close	Close	Close	**On**

Note: Computer controlled relay and fuel valve relay are normally open

The ladder logic diagrams for low voltage circuit, used to actuate the power relays, and for the 120V operating circuit are given in Figures I-1. The diagrams for camera, calorimeter pump and fuel pump operation are shown in Figures I-2. The control system is summarised in Boolean algebra below:

Vapour vent valve $= P_o \cdot P_c \cdot \left(PB_1 \cdot S_3 + RC_3 \cdot S_4\right)$

Liquid drain valve $= P_o \cdot P_c \cdot PB_2 \cdot S_5$

$V_F = \overline{P_o \cdot P_c \cdot RC_2 \cdot S_2}$

Pump $= P_o \cdot P_c \cdot \overline{V_F} \cdot RC_1 \cdot S_1$

Spark Igniter $= RC_4$

Ignition fuel valve $= \overline{RC_5}$

Calorimeter pumps $= RC_{6,7,8}$

$V_W = RC_{10}$

Water Pump $= \mathrm{V_W} \cdot RC_9$

V_F = Fuel supply valve

1 = Valve closed

0 = Valve open

$\mathrm{P_o}$ = Operating power (0 = Off, 1 = On)

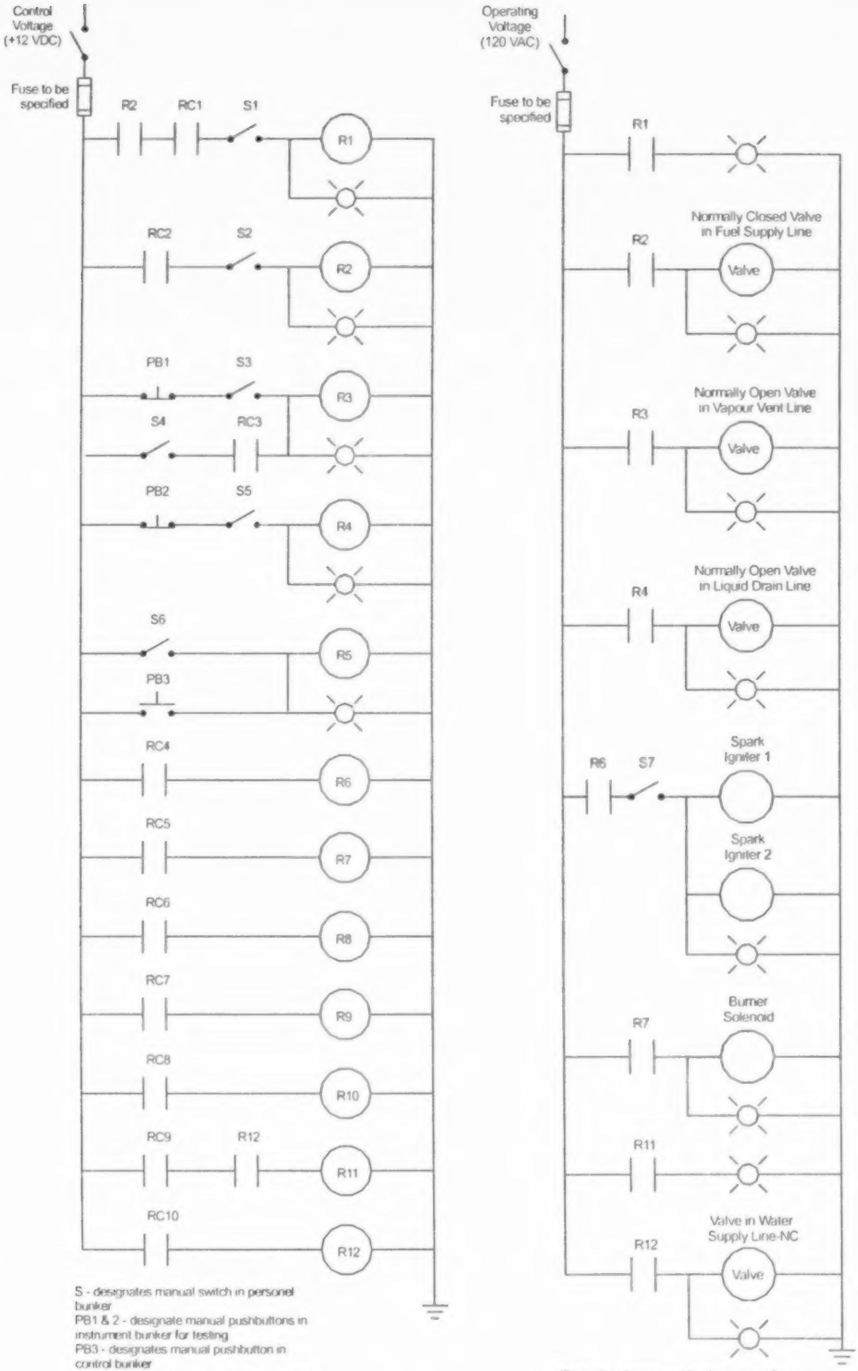
$\mathrm{P_c}$ = Control power (0 = Off, 1 = On)

PB = Push button in instrument bunker (0 = Open, 1 = Closed)

S = Toggle switch in personnel bunker (0 = Open, 1 = Closed)

RC = Computer controlled relay (0 = Not powered, 1 = Powered)

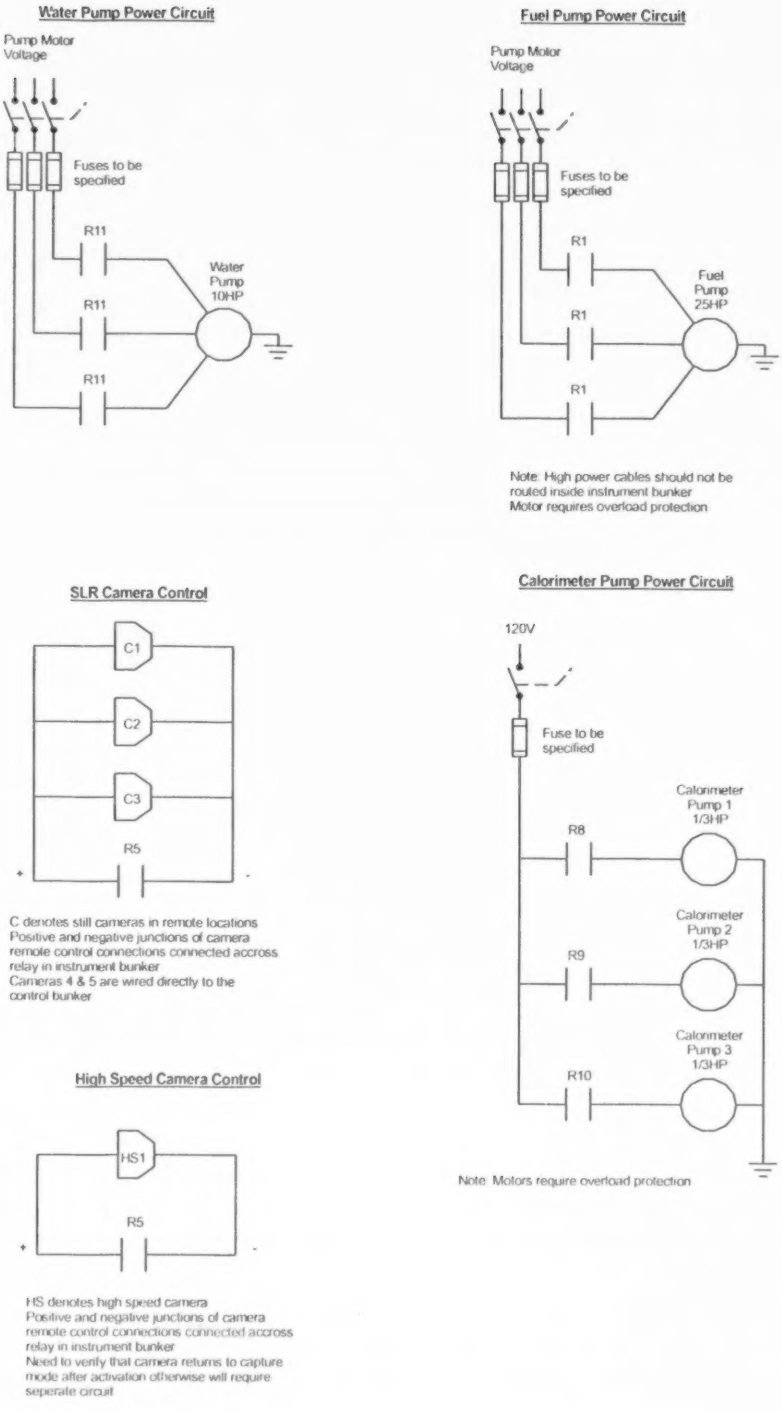
Numbering relays, switches and pushbuttons corresponds to control diagram


Control Voltage (+12 VDC)
Fuse to be specified
R2
RC1
S1
R1
RC2
S2
R2
PB1
S3
R3
S4
RC3
PB2
S5
R4
S6
R5
PB3
RC4
R6
RC5
R7
RC6
R8
RC7
R9
RC8
R10
RC9
R12
R11
RC10
R12
Operating Voltage (120 VAC)
Fuse to be specified
R1
Normally Closed Valve in Fuel Supply Line
R2
Valve
Normally Open Valve in Vapour Vent Line
R3
Valve
Normally Open Valve in Liquid Drain Line
R4
Valve
R6
S7
Spark Igniter 1
Spark Igniter 2
Burner Solenoid
R7
R11
Valve in Water Supply Line-NC
R12
Valve

S - designates manual switch in personel bunker
PB1 & 2 - designate manual pushbuttons in instrument bunker for testing
PB3 - designates manual pushbutton in control bunker
RC - desigantes relay controlled by computer DAC system
Indicator lights are in control bunker
Relays are in instrument bunker except R1, R8, R9, R10, R11 which are in field near pumps

Controls in instrument bunker except for R1, R11 and S6
R1 and R11are near fuel and water pumps
S7 is in field in sight of propane burners
120V cables should be shielded

Figure I-1: Ladder logic control diagram for safe strategy showing control circuit and 120V operating circuit



Water Pump Power Circuit

Fuel Pump Power Circuit

Note: High power cables should not be routed inside instrument bunker
Motor requires overload protection

SLR Camera Control

C denotes still cameras in remote locations
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Cameras 4 & 5 are wired directly to the control bunker

Calorimeter Pump Power Circuit

Note: Motors require overload protection

High Speed Camera Control

HS denotes high speed camera
Positive and negative junctions of camera remote control connections connected accross relay in instrument bunker
Need to verify that camera returns to capture mode after activation otherwise will require seperate circuit

Pump Motor Voltage
Fuses to be specified
R11
R11
R11
Water Pump 10HP
Pump Motor Voltage
Fuses to be specified
R1
R1
R1
Fuel Pump 25HP
C1
C2
C3
R5
+
-
120V
Fuse to be specified
Calorimeter Pump 1 1/3HP
R8
Calorimeter Pump 2 1/3HP
R9
Calorimeter Pump 3 1/3HP
R10
HS1
R5
+
-

Figure I-2: Ladder logic control diagram for safe strategy showing camera and pump operating circuits

Maximum Test Robustness

This control system is designed to allow the test to continue and does not necessarily default to the safest condition. The valves on the vapour release and liquid drain are normally closed. If the power fails the valves will close, retaining all the propane and pressure in the tank-car, allowing for a restart or retest.

The power relays controlling the valves are activated through the following controls in parallel:

- Manual toggle switch in control bunker – closing this will open valve.
- Normally open pushbutton in instrument bunker – for testing valve pressing this button will open the valve.

If the control power supply fails the power relay opens, cutting of power to the valves which then close. If the power electrical supply fails the valves close. Both the vapour and liquid drain systems also have a manual valve that would be in the closed position until just prior to the test. The actions of the valves are summarised in Table I-5 for the liquid drain and Table I-6 for the vapour vent.

The fuel control system is operated by the computer, but can be overridden manually. The fuel control valve is activated to both open and closed positions so that if power fails it will remain in its current position. The fuel pump will obviously stop operating if the power fails.

The power relay opens the fuel valve through normally closed switches and closes it through normally open. The relay is activated through the following controls in series:

- Manual toggle switch in control bunker – this must be closed to close the valve.
- Normally open computer controlled relay in parallel with a manual toggle switch in control bunker – one must be closed to close the valve.

If the control electrical supply fails the power relay opens, powering the valve open. If the power supply fails the valve remains in its current position. The action of the fuel valve is summarised in Table I-7.

The fuel pump relay is normally open and needs to be powered for pump operation. It is powered by the following controls in series:

- Normally closed switch on fuel valve relay – ensures pump does not operate if valve is closed.
- Normally open computer controlled relay – must be powered operate pump.
- The above relays can be by-passed with a toggle switch in the control bunker.
- Manual toggle switch in control bunker – this must be closed to run the pump.

The action of the fuel pump is summarised in Table I-8.

The controls for the ignition system, calorimeter and cameras are the same as for the safe strategy. The water make up system is not used. This could increases the time required to stop the test, since any water evaporated is replaced with fuel, but removes the possibility of the test aborting due to the fuel layer being displaced by the water. This could occur if the water pump did not shut down. The fuel control system would not differentiate between fuel and water and would not start delivering fuel, which would burn-off and end the test prematurely.

Table I-5: Control status for liquid drain valve for robust strategy

Operating Power	Control Power	Instrument Bunker Pushbutton	Control Bunker Toggle Switch	Valve Position
Off	On/Off	Open/Close	Open/Close	**Close**
On	Off	Open/Close	Open/Close	**Close**
On	On	Close	Open/Close	**Open**
On	On	Open/Close	Close	**Open**
On	On	Open	Open	**Close**

Note: Pushbutton is normally open

Table I-6: Control status for vapour vent valve for robust strategy

Operating Power	Control Power	Instrument Bunker Pushbutton	Control Bunker Toggle Switch	Computer Controlled Relay	Valve Position
Off	On/Off	Open/Close	Open/Close	Open/Close	**Close**
On	Off	Open/Close	Open/Close	Open/Close	**Close**
On	On	Close	Open/Close	Open/Close	**Open**
On	On	Open/Close	Close	Open/Close	**Open**
On	On	Open/Close	Open/Close	Close	**Open**
On	On	Open	Open	Open	**Close**

Note: Pushbutton is normally open

Table I-7: Control status for fuel supply valve for robust strategy

Operating Power	Control Power	Computer Controlled Relay	Control Bunker Toggle Switch 2	Control Bunker Toggle Switch 3	Valve Position
Off	On/Off	Open/Close	Open/Close	Open/Close	**Remains in current position**
On	Off	Open/Close	Open/Close	Open/Close	**Open**
On	On	Open/Close	Open	Open/Close	**Open**
On	On	Open	Open/Close	Open	**Open**
On	On	Close	Close	Open/Close	**Close**
On	On	Open/Close	Close	Close	**Close**

Note: Computer controlled relay is normally open

Table I-8: Control status for fuel pump for robust strategy

Operating Power	Control Power	Fuel Valve Relay	Computer Controlled Relay	Control Bunker Toggle Switch 1	Control Bunker Toggle Switch 8	Pump Status
Off	On/Off	Open/Close	Open/Close	Open/Close	Open/Close	**Off**
On	Off	Open/Close	Open/Close	Open/Close	Open/Close	**Off**
On	On	Open/Close	Open/Close	Open	Open/Close	**Off**
On	On	Open/Close	Open/Close	Close	Close	**On**
On	On	Close	Close	Close	Open/Close	**On**
On	On	Open	Open/Close	Open/Close	Open	**Off**
On	On	Open/Close	Open	Open/Close	Open	**Off**

Note: Computer controlled relay is normally closed and fuel valve relay is normally open

The ladder logic diagrams for low voltage circuit, used to actuate the power relays, and for the 120V operating circuit are given in Figures I-3. The diagram for the cameras, calorimeters and fuel pump operation are the same as for the safe strategy, and are shown in Figures I-2. The control system is summarised in Boolean algebra below:

Vapour vent valve = $\overline{P_o \cdot P_c \cdot (PB_1 + S_4 + RC_3)}$

Liquid drain valve = $\overline{P_o \cdot P_c \cdot (PB_2 + S_5)}$

$V_{F,Open} = P_o \cdot \overline{P_c \cdot (RC_2 + S_3) \cdot S_2}$

$V_{F,Closed} = P_o \cdot P_c \cdot (RC_2 + S_3) \cdot S_2$

Pump = $P_o \cdot P_c \cdot (V_{F,Open} \cdot RC_1 + S_8) \cdot S_1$

Spark Igniter = RC_4

Ignition fuel valve = RC_5

Calorimeter pumps = $RC_{6,7,8}$

$V_{F,position}$ = Fuel supply valve - actuated to indicated position when = 1

1 = Vapour vent or liquid drain valve closed

0 = Vapour vent or liquid drain valve open

P_o = Operating power (0 = Off, 1 = On)

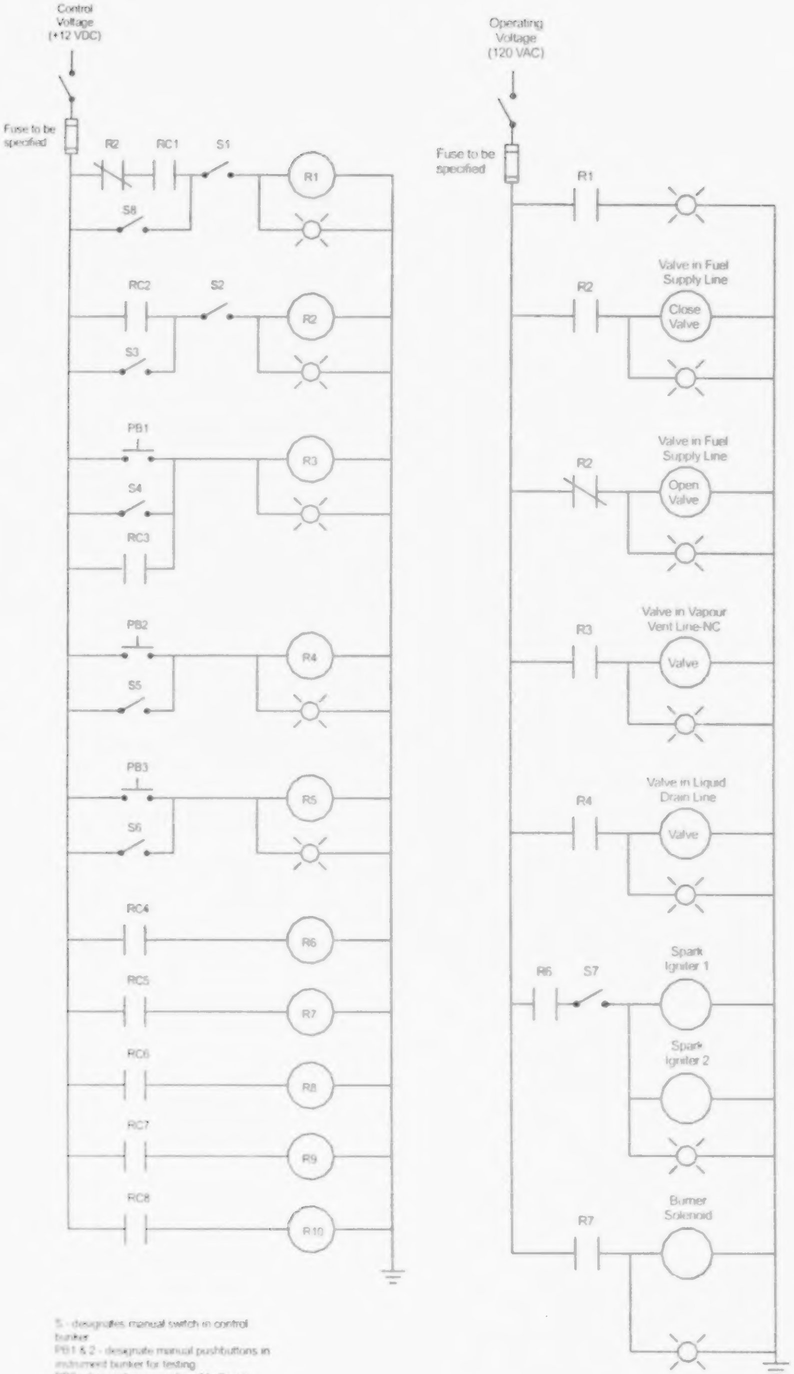
P_c = Control power (0 = Off, 1 = On)

PB = Push button in instrument bunker (0 = Open, 1 = Closed)

S = Toggle switch in personnel bunker (0 = Open, 1 = Closed)

RC = Computer controlled relay (0 = Not powered, 1 = Powered)

Numbering relays, switches and pushbuttons corresponds to control diagram


Control Voltage (+12 VDC)
Fuse to be specified
R2
RC1
S1
R1
S8
RC2
S2
R2
S3
PB1
R3
S4
RC3
PB2
R4
S5
PB3
R5
S6
RC4
R6
RC5
R7
RC6
R8
RC7
R9
RC8
R10
Operating Voltage (120 VAC)
Fuse to be specified
R1
Valve in Fuel Supply Line
R2
Close Valve
Valve in Fuel Supply Line
R2
Open Valve
Valve in Vapour Vent Line-NC
R3
Valve
Valve in Liquid Drain Line
R4
Valve
R6
S7
Spark Igniter 1
Spark Igniter 2
Burner Solenoid
R7
Valve

S - designates manual switch in control bunker
PB1 & 2 - designate manual pushbuttons in instrument bunker for testing
PB3 - designates manual pushbutton in control bunker
RC - designates relay controlled by computer DAC system
Indicator lights are in control bunker
Relays are in instrument bunker

Controls in instrument bunker except for R1 and S7
R1 is near fuel pump
S7 is in field in sight of burners
120V cables should be shielded

Figure I-3: Ladder logic control diagram for robust strategy showing control circuit and 120V operating circuit